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Interactions between landslides, land use and management: a case study on the Rift flanks west of Lake Kivu (DR Congo)

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A

ma très chère tendre épouse Orléanne

nos très chers enfants Ethan et Ysaline

mes très chers parents Jean-Pierre Mateso et Jeanne Dhimbe

mes frères et sœurs Jean-Paul, Roger, Nicole,

Valéry, Eugénie, Alain et Aline

« Confie-toi en l'Eternel de tout ton cœur

et ne t'appuie pas sur ton intelligence!

Reconnais-le dans toutes tes voies

et il rendra tes sentiers droits ».

Proverbes 3:5-6

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Résumé

Les régions montagneuses tropicales sont souvent identifiées comme des zones sensibles aux glissements de terrain en raison de la pression démographique croissante. Cependant, très peu d'informations sont disponibles pour comprendre les processus de glissement de terrain dans ces environnements. Cette thèse étudie les interactions entre les glissements de terrain et l'utilisation et la gestion des terres dans un environnement rural situé sur les flancs du Rift à l'ouest du lac Kivu (RD Congo). Des approches multi-méthodes, combinant la télédétection et les travaux de terrain, nous ont permis : (1) d'analyser, à l'échelle régionale, la distribution des différentes catégories de glissements de terrain et d'identifier les facteurs de leur prédisposition ; (2) d'étudier, à l'échelle locale, les facteurs qui déterminent l'utilisation des terres sur les glissements de terrain après leur occurrence ; et (3) de quantifier le taux de changement du couvert végétal dans les zones affectées par les glissements de terrain et d'analyser les facteurs environnementaux qui déterminent la végétalisation après un événement pluvieux intense et convectif déclenchant des glissements de terrain et des crues soudaines. A l'échelle régionale (5700 km²), un inventaire unique pour ce type d'environnement a été construit, avec plus de 2730 glissements de terrain cartographiés. Nous avons identifié les glissements de terrain anciens et récents (post 1950), en distinguant les glissements de terrain profonds et superficiels, les glissements de terrain liés aux routes et ceux liés aux mines. Les analyses des statistiques des distributions de tailles et des facteurs prédisposants par les modèles de susceptibilité montrent que : (1) les glissements de terrain profonds anciens et récents sont différents entre eux ; ce qui montre que les facteurs naturels contribuant à leur apparition ont été soit différents, soit modifiés au fil du temps ; (2) les glissements de terrain superficiels sont plus fréquents, mais de plus petite taille, dans les zones où la déforestation a eu lieu depuis les années 1950 par rapport aux glissements de terrain superficiels dans les zones forestières, i. (3) les glissements de terrain liés aux mines et ceux liés aux routes sont de plus grande taille que les glissements de terrain superficiels mais plus petits que les glissements de terrain profonds récents ; et ils sont contrôlés par des facteurs environnementaux différents des conditions naturelles d'occurrence. À l'échelle locale, les enquêtes sur le terrain et l'analyse spatiale ont montré que les affectations du sol pour les cultures sont plus dominantes sur les glissements de terrain que sur les versants adjacents, ce qui reflète la forte pression démographie sur la demande des terres agricoles. Les trois quarts des agriculteurs interrogés savaient qu'ils travaillaient sur un glissement de terrain et 89 % d'entre eux évaluent actuellement le risque de réactivation comme élevé à très élevé. La satisfaction des agriculteurs et la valeur des terres situées à l'intérieur des glissements de terrain peuvent être plus élevées que celles des terres adjacentes lorsque les glissements de terrain sont caractérisés par une plus grande fertilité, des pentes plus faibles, un terrain moins pierreux et sablonneux, un sol plus profond et une plus grande humidité. Ces conditions naturelles favorables sont généralement plus présentes sur les glissements de terrain profonds, anciens, de grande taille et ceux à mouvement « glissement » que sur leurs flancs adjacents. En analysant l'événement pluvieux, d'octobre 2014, déclenchant des glissements de terrain et des crues soudaines dans les environs de Kalehe, pris comme étude de cas, il a été constaté que les zones sources des glissements superficiels, sur des pentes plus raides, se végétalisent plus lentement que les zones de dépôt et de transport (secteur de propagation). Pour ces dernières, la vitesse de reprise de la végétation est affectée par la raideur de la pente et par l'exploitation des terres et des débris mobilisés lors de l'événement à des fins de construction. La recherche doctorale a montré qu'au-delà des prédispositions naturelles, l'activité humaine joue un rôle important en tant que facteur de prédisposition et, dans la période post-événement, dans le changement d'utilisation des terres et du couvert végétal. Pour une meilleure stratégie de réduction des risques dans les environnements tropicaux, il est nécessaire d'entreprendre d'autres études et actions pour minimiser l'impact humain dans les occurrences des glissements de terrain, plus spécialement, avec la préservation et la restauration de la couverture forestière et l'aménagement du territoire.

Abstract

Tropical mountainous regions are often identified as landslide hotspots because of the growing population pressure. However, very little information is available for understanding landslide processes in these environments. This thesis investigates the interactions between landslides and land use and management in a rural environment located on the Rift flanks west of Lake Kivu (DR Congo). Multi-method approaches, combining remote sensing and field work, allowed us: (1) to analyze, at the regional scale, the distribution of the different categories of landslides and to identify the factors that favour their occurrence; (2) to investigate, at the local scale, the factors that drive land use on landslides after their occurrence; and (3) to quantify the rate of vegetation cover change in landslide-affected zones and analyze the environmental factors that drive revegetation after an intense convective rainfall event triggered landslides and flash floods. At the regional scale (5700 km^2), a unique inventory for this type of environment was built, with more than 2730 landslides mapped. We identified old and recent (post 1950's) landslides, making a distinction between deep-seated and shallow landslides, road landslides and mining landslides. Analyses of frequency-area statistics and predisposing factors by susceptibility models show that: (1) susceptibility patterns and area distributions are different between old and recent deep-seated landslides, which shows that natural factors contributing to their occurrence were either different or changed over time; (2) shallow landslides are more frequent, but of smaller size, in areas where deforestation has occurred since the 1950's as compared to shallow landslides in forest areas, i.e. in natural environments ; and (3) mining-related landslides and road-related landslides are larger than shallow landslides but smaller than recent deep-seated landslides; and they are controlled by environmental factors different from the natural conditions of occurrence. At the local scale, field surveys and spatial analysis showed that farming is more common on landslides than on adjacent flanks, reflecting the strong human demand for agricultural land. Three quarters of the surveyed farmers were aware that they operate on a landslide and 89% of them currently assess the risk of reactivation as high to very high. Farmer satisfaction and the value of land inside landslides can be higher than adjacent land when they are characterized by higher fertility, weaker slopes, less stony and sandy terrain, deeper soil and greater moisture. These favourable natural conditions are generally more prevalent on deep-seated, old, large, "landslides" than on their adjacent flanks. Using the combined landslide-flash flood event of October 2014 in the vicinity of Kalehe as a case study, it was found that the source zones for the shallow landslides, on steeper slopes, revegetate more slowly than the transport-deposit zones (propagation sector). For the latter zones, the rate of vegetation recovery is affected by slope steepness and by the exploitation of earth and debris mobilized during the event for construction purposes. The doctoral research showed that, beyond natural predispositions, human activity plays an important role as a predisposing factor and, in the post-event period, in land use and vegetation cover change. For a better risk reduction strategy in tropical environments, there is a need to undertake further studies and actions to minimize the human impact on landslide occurrences, especially in the preservation and restoration of forest cover and land use planning.

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-	ANOVA	Analysis of Variance (statistical models)
-	AUC	Area Under the Curve
-	CCI	ESA's Climate Change Initiative
-	CNES	Centre National d'Etudes Spatiales
-	CRSN	Centre de Recherche en Sciences Naturelles
-	DEM	Digital Elevation Model
-	DR Congo	Democratic Republic of Congo
-	DRR	Disaster Risk Reduction
-	ECGS	European Center for Geodynamics and Seismology
-	ESA	European Space Agency
-	FN	False Negative
-	FOMULAC	Fondation Médicale de l'Université de Louvain au Congo
-	FP	False Positive
-	GH	Geo-hydromorphologic
-	GPM	Global Precipitation Measurement
-	IBM	International Business Machines Corporation
-	IMERG	Integrated Multi-satellitE Retrievals for GPM
-	ISC	International Seismological Centre
-	LS	Landslide
-	LULC	Land Use and Land Cover
-	Mb	Body-wave Magnitude
-	MCA	Multiple Correspondence Analysis
-	MODIS	Moderate-Resolution Imaging Spectroradiomete
-	MSI	Sentinel-2's MultiSpectral Instrument
-	NASA	National Aeronautics and Space Administration

-	NDVI	Normalized Difference Vegetation Index
-	NGO	Non-Governmental Organization
-	NTK	Rift North Tanganyika-Kivu Rift region
-	OR	Odds Ratio
-	OVG	Observatoire Volcanologique de Goma (RD Congo)
-	PNKB	Kahuzi-Biega National Park
-	RMCA	Royal Museum for Central Africa
-	ROC	Receiver Operating-characteristics Curve
-	SPSS	Statistical Package for the Social Sciences
-	SRTM	Shuttle Radar Topography Mission
-	TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement
-	TP	True Positive
-	TWI	Topographic Wetness Index
-	UCLouvain	Université catholique de Louvain
-	UNESCO	United Nations Educational, Scientific and Cultural Organization
-	UNISDR	United Nations International Strategy for Disaster Reduction
-	USGS	United States Geological Survey
-	VIF	Variance Inflation Factor

Chapter 1

Introduction générale

"Knowledge is the key to survival, the real beauty of that is that it doesn't weigh anything."

Ray Mears

"La connaissance est la clé de la survie, la vraie beauté de ça, c'est que ça ne pèse rien."

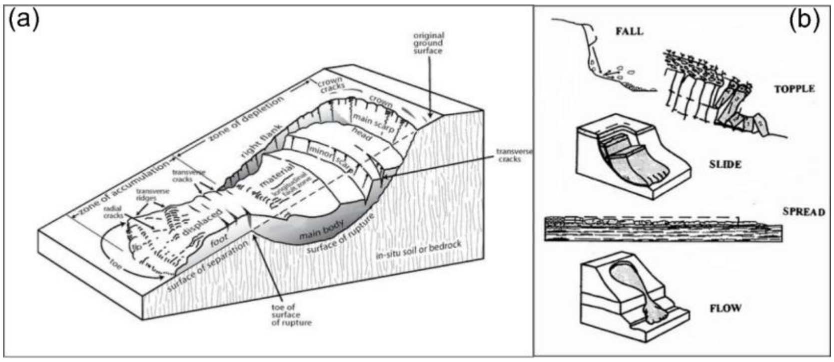
1.1 Importance de la problématique des glissements de terrain dans le monde

Le monde est actuellement confronté aux enjeux liés aux changements climatiques globaux et à des mutations socio-économiques et environnementales, telles que le changement des affectations du sol, la déforestation, la relocalisation des populations, la pression foncière due à l'expansion urbaine, l'exploitation des ressources minières, etc (Susman et al., 2019; UNCCD, 2022). Ces diverses perturbations exposent les populations aux catastrophes naturelles lorsque les aléas surviennent (Susman et al., 2019; UNCCD, 2022). Parmi ces aléas, les pluies intenses et les tremblements de terre peuvent, de manière indépendante ou dans une chaîne plus large d'aléas en cascade, déclencher des glissements de terrain (Marc et al., 2018; Emberson et al., 2020; voir encadré relatif aux concepts clés associés aux glissements de terrain). Ces glissements de terrain façonnent les paysages, érodent les chaines de montagnes, transportent les sols et les roches (Guzzetti et al., 2012; Gill and Malamud, 2014; Sidle and Bogaard, 2016; Fan et al., 2019; Campforts et al., 2020). Ils sont une source majeure de dégradation des sols et de leurs nombreux services écosystémiques (Sidle and Bogaard, 2016; Adhikari and Hartemink, 2016). Les glissements de terrain sont aussi une source importante de sédiments avec des conséquences sur la qualité des eaux (Mackey and Roering, 2011; Walker and Shiels, 2013; Campforts et al., 2020). Les occurrences temporelles et spatiales des glissements de terrain résultent des changements environnementaux dus souvent aux prédispositions naturelles (topographiques et/ou lithologiques) et, parfois, celles liées aux activités humaines. Dans certains cas, les activités humaines sont considérées comme de facteur causal d'importance égale, voire supérieure, aux facteurs naturels (Crozier, 2010; Froude and Petley, 2018). A travers le monde, les glissements de terrain sont classés parmi les cinq premiers aléas les plus dommageables en termes de fréquence (CRED, 2015; Rosselló et al., 2020). Les estimations des impacts des glissements de terrain suggèrent qu'ils causent des milliers de décès (près des 5000 morts pour les glissements de terrain d'origine hydrologique) chaque année (Petley, 2012; Froude and Petley, 2018) et des milliards de dollars de dommages économiques (Dilley et al., 2005; Sim et al., 2022).

Quelques concepts clés

I. Concepts sur les glissements de terrain

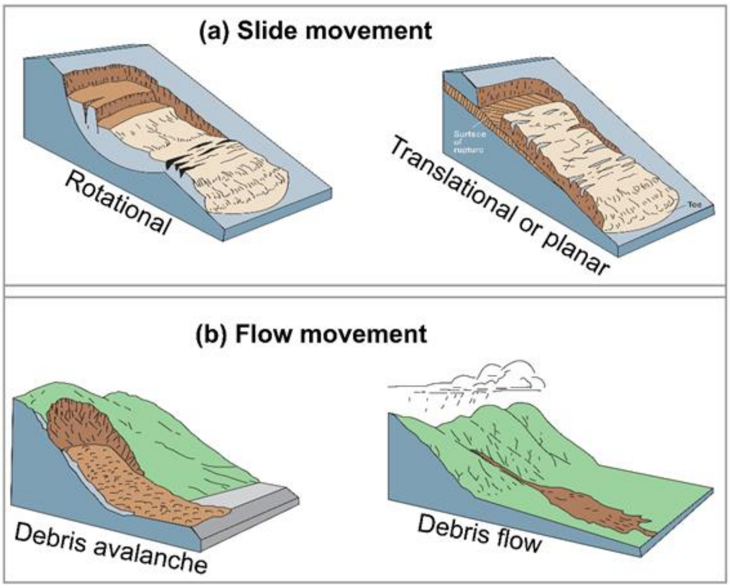
Les glissements de terrain sont des processus qui ont lieu sous l'effet principal de la gravité et se caractérisent par des descentes de masses de roche, de terre ou de débris le long d'une surface de rupture (Cruden, 1991). Un glissement de terrain est subdivisé en trois grandes zones à savoir la zone (ou secteur) source ou d'initiation, la zone de transport et la zone d'accumulation des matériaux (Fig.1a). Suivant la profondeur de la zone source, les glissements de terrain sont classés comme profonds si la profondeur est supérieure à 5 m ; sinon, il s'agit des glissements de terrain superficiels (Keefer 1984; Bennett et al. 2016; Sidle and Bogaard 2016). Les glissements de terrain superficiels peuvent être stabilisés par la couverture végétale dans des conditions liées au gradient de la pente en place, des propriétés mécaniques du sol (texture, structure, etc.) et de la distribution du système racinaire qui dépend de l'espèce végétale (Schmidt et al. 2001; Schwarz et al. 2010; Löbmann et al. 2020). Par contre, l'action du système racinaire des arbres est quasi nulle pour stabiliser les glissements de terrain profonds notamment lors d'une réactivation à la suite de fortes pluies ou d'activités sismiques (Forbes et al., 2013).



a) Bloc diagramme d'un glissement de terrain complexe idéalisé d'après Varnes (1978) and Varnes (1978) modifié par © (Guadalupe, 2018). b) Types de mouvements d'après Cruden and Varnes (1996).

Cruden and Varnes (1996) classent les types de mouvement des matériaux (sols ou blocs de pierre) en cinq types, dont: chute (fall), basculement (topple), glissement (slide), fluage ou reptation (spread) and coulée (flow) (Fig. 1b). Hungr et al. (2014) proposent, dans une mise à jour de la classification de Cruden and Varnes (1996), l'ajout du mouvement slope deformation (déformation de la pente) ; ce dernier se manifeste par une déformation à grande échelle sans surface de rupture pleinement définie et dont les vitesses de déplacement sont extrêmement lentes ou non mesurables.

La présente recherche doctorale ne prend en compte que les mouvements glissement (slide) et coulée (flow). Les autres mouvements (fall, topple, spread and slope deformation) sont exclus de l'inventaire final car ils sont rares pour constituer un inventaire suffisamment élevé pour leurs analyses. En plus, le modèle numérique de terrain SRTM (30 m de résolution), utilisé pour calculer les valeurs des facteurs topographiques supposés contribuer à leur occurrence, n'est pas indiqué soit en raison de leur trop grande taille pour le slope deformation ou de leur pente raide pour les mouvements fall et topple ou encore la surface plane sur laquelle évolue le mouvement spread. En outre, les mouvements exclus sont difficilement détectables sur les images satellitaires comme celles de © Google Earth ayant servi pour la cartographie de base des glissements de terrain.



Les mouvements « slide et flow » se différencient par leur cinématique. Le mouvement slide (Fig. 2a) comprend le slide rotational et le slide translational ou planar qui sont caractérisés, respectivement, par des vitesses lentes (plusieurs mois voir années) à rapides (à l'espace de quelques minutes ou heures) (Hungr et al., 2014). Au milieu du glissement de terrain rotationnel, la surface de rupture de pente se déplace moins vite et lui confère une certaine stabilité mais avec des lentes déformations continues. Par contre, le slide translational présente peu ou pas de déformation interne mais évolue rapidement sur sa surface de rupture et sa vitesse devient rapide sur les fortes pentes pouvant se transformer en mouvement flow (comme le « debris avalanche », Fig. 2b) (Hungr et al., 2014). Le mouvement flow (Fig. 2b) est très rapide, voir extrêmement rapide (quelques minutes à heures), et ses matériaux (sol ou blocs de pierre) peuvent déboucher dans le talweg abrupt dans la zone de montagne et se mélanger aux eaux d'écoulement pour se transformer en une crue éclair destructive appelée « debris flow » traduite comme coulée des débris (Hungr et al., 2014).

II. Concepts complémentaires

II.1. Mise en valeur d'un glissement de terrain (landslide valorization)

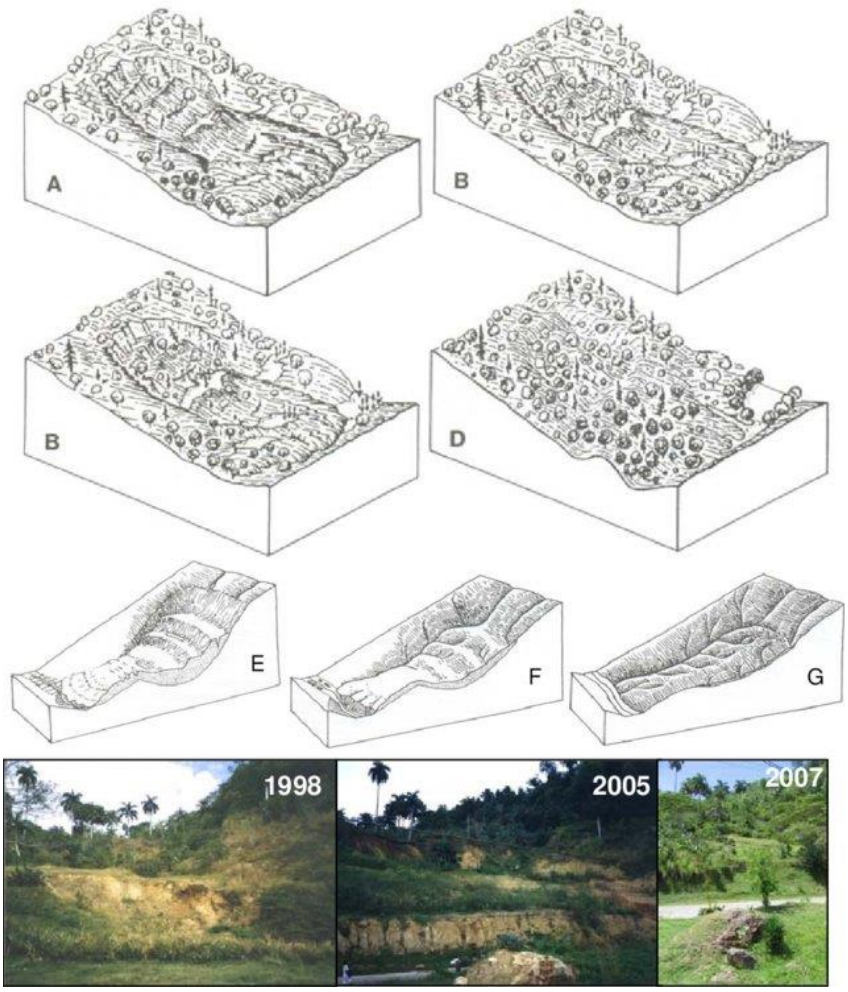
Dans le cadre de cette recherche doctorale, nous analysons les utilisations de terres au sein des glissements de terrain après leurs occurrences. En effet, les différentes zones d'un glissement de terrain peuvent offrir des conditions écologiques variables propices aux utilisations des terres différenciées et voire même des établissements humains sur les zones de topographie en pentes faibles en régions montagneuses (Walker and Shiels, 2013; Alexandrowicz and Margielewski, 2010; Temme, 2021).

II.2. Anthropisation (anthropization)

L'anthropisation désigne la modification d'un milieu dit « naturel » par les activités humaines. On peut aussi parler d'artificialisation ; mais ce terme désigne plutôt un état avancé d'anthropisation. L'anthropisation est un processus, le résultat est un milieu anthropisé (http://geoconfluences.ens-lyon.fr/glossaire/anthropisation; consulté le 13/01/2023).

II. 2. Végétalisation (revégétalisation)

Il s'agit du rétablissement de plantes naturel ou volontaire par la replantation sur une zone de terrain appauvrie ou dépourvue de végétation, afin d'assurer une protection contre les agents érosifs (Goodier, 2016). Elle fait partie intégrante du contrôle et de la prévention de l'érosion sur une grande variété de terrains perturbés, érodés et/ou dégradés(Broadhurst et al., 2008; Goodier, 2016).



Végétalisation des glissements de terrain et leur datation (Figure prise de Castellanos Abella, 2008). Diagrammes A-D pour la végétalisation sous climat humide (d'après Wieczorek, 1984), diagrammes E-G pour climat aride ou semi-aride (d'après McCalpin, 1984). Les photos dans la partie inférieure représentent la végétalisation d'un même glissement de terrain en différentes années (Castellanos Abella, 2008).

1.2 Glissements de terrain en zone tropicale montagneuse

Très peu d'informations sont disponibles sur les processus des glissements de terrain dans les tropiques car peu d'événements sont rapportés (estimés entre 0 à 16 en Afrique pour la période de 1900 à 2022 ; source : https://public.emdat.be/mapping, consulté le 13 janvier 2023) et cela crée une limitation dans la compréhension de l'exposition aux glissements de terrain dans les pays en développement (Emberson et al., 2020). Dans ces régions, les études concernent, très souvent, des régions limitées (< 1000 km^2) (Reichenbach et al., 2018).

Dans les régions tropicales d'Amérique du Sud (les montagnes des Andes entre Venezuela et Bolivie et l'est du Brésil) et Centrale (Costa Rica et le Sud du Mexique), les inventaires sur les glissements de terrain sont variés suivant les échelles, les méthodologies de compilation, les informations temporelles et les précisions (Kirschbaum et al., 2015; Valdés Carrera et al., 2021). Ces inventaires couvrent les glissements de terrain déclenchés lors des cyclones et les glissements historiques en recourant aux photographies, à la télédétection et aux observations de terrain (e.g. : Alcántara-Ayala et al., 2006; Guns and Vanacker, 2013; Froude and Petley, 2018; Palacio Cordoba et al., 2020). Les facteurs de prédisposition de ces glissements de terrain ont été analysés ; et la dynamique du changement de la couverture du sol joue un rôle important dans les occurrences de ces glissements de terrain (Alcántara-Ayala et al., 2006; Guns and Vanacker, 2014). En général, la revue de la littérature rapporte que, entre 2000 et 2019, les études sur les glissements de terrain se sont plus axées sur la susceptibilité et la caractérisation des glissements de terrain et moins sur la validation des inventaires sur le terrain, la dangerosité, la compréhension sur le terrain de prédisposition (Valdés Carrera et al., 2021).

Les régions d'Asie centrale situées le long de l'Himalaya, l'Inde, le Sud-Est chinois, le Laos, Bangladesh, l'Indonésie, les Philippines et les pays voisins représentent le nombre d'événements des glissements de terrain les plus élevés du monde avec des dommages importants (Froude and Petley, 2018). En général, les études sur les glissements de terrain sont en nombre croissant après 2010, et ces études analysent les conditions de déclenchement et les facteurs de prédisposition dont les interventions humaines (Khasanov et al., 2021).

En Océanie dans la région tropicale d'Australie et en Nouvelle-Guinée, les inventaires et les analyses de la susceptibilité sont parmi les moins poussés au monde (Reichenbach et al., 2018). En Papouasie-Nouvelle-Guinée, les glissements de terrain déclenchés par les tremblements de terre et les pluies diluviennes ont des impacts socio-économiques importants auprès des communautés vulnérables et des investissements miniers. Dans cette région, les études portent essentiellement sur les conditions de déclenchement (Robbins and Petterson, 2015; Robbins, 2016; Tanyaş et al., 2022b) et la susceptibilité suivant des approches méthodologiques variables (Samanta and Bhunia, 2013; Jana et al., 2019; Tanyaş et al., 2022b). En région australienne tropicale, la littérature renseigne très peu sur les glissements de terrain à part l'étude de Puga-Bernabéu et al. (2022) qui ont travaillé sur la morphométrie des glissements de terrain sous-marins, dans la Grande Barrière de corail.

En Afrique, les études sur les glissements de terrain sont jusque-là rares (Reichenbach et al., 2018) avec des inventaires hétérogènes notamment (Froude and Petley, 2018). Ces dernières années, les études, sur les inventaires et les susceptibilités se font à différentes échelles et les méthodologies abordées sont variées (Zogning et al., 2007; Romer and Ferentinou, 2016; Broeckx et al., 2018; Jacobs et al., 2018; Monsieurs et al., 2018a; Depicker et al., 2020; Rault et al., 2022). Les études en Afrique sont éparses pour plusieurs raisons dont la faible cartographie d'inventaire des glissements de terrain, l'inaccessibilité de plusieurs zones, le manque de données de base à l'échelle locale ou régionale (météorologie, télédétection) etc. Les données de base les plus accessibles sont à l'échelle globale à partir des nombreux produits satellitaires (notamment hébergés sur Google Earth Engine : https ://developers.google.com/earth-engine/datasets/, consulté le 13/01/2023); lesquels sont à des résolutions non suffisantes pour des études à l'échelle locale ni régionale. L'Afrique centrale, notamment sur le rift est africain (région des grands lacs), connait des occurrences des glissements de terrain en raison de la topographie montagneuse, des pluies intenses et d'un manteau d'altération épais avec des lourdes conséquences en raison des fortes densités et des vulnérabilités élevées (Kervyn et al., 2015). En Afrique centrale, les études sur les glissements de terrain ont commencé, peu avant 2015, sur différentes échelles. A l'échelle régionale, les études ont été menées sur les inventaires, essentiellement basés sur les interprétations des imageries satellitaires, et sur les susceptibilités, sans en distinguer ceux qui sont naturels et anthropiques, ni suivant leurs âges relatifs récents ou anciens (e.g : Knapen et al., 2006; Jacobs et al., 2016a; Nsengiyumva et al., 2018; Kubwimana et al., 2021). A l'échelle locale, les études sur les glissements de terrain ont portées, notamment, sur le cadre géomorphologique d'étude de cas (Mugaruka Bibentyo et al., 2017; Nobile et al., 2018; Dille et al., 2019; Dille et al., 2022) et sur les enquêtes de terrain auprès des menages pour la compréhension des impacts et des stratégies de réduction des risques (e.g: Mertens et al., 2016; Michellier et al., 2016; Osuret et al., 2016; Masaba et al., 2017). La littérature ne nous renseigne pas de manière explicite sur les implications des changements d'utilisation de sol sur le long terme, des activités minières et des constructions des routes dans les occurrences des glissements de terrain. A l'échelle locale, des questions peuvent être analysées sur les occupations du sol et la temporalité du changement de couverture végétale des glissements de terrain après leur déclenchement.

En raison de la couverture spatiale des inventaires des glissements de terrain et les analyses des facteurs de prédispositions, il apparait que l'Afrique, l'Amérique du Sud et Centrale et l'Océanie sont encore moins étudiées par rapport à l'Asie (Froude and Petley, 2018; Reichenbach et al., 2018). En effet, il y a lieu que des études plus détaillées soient menées sur la compréhension des processus de glissements de terrain dans ce monde tropical, notamment en fournissant des inventaires plus détaillés. Cette nécessité est plus accrue dans les pays en développement qui sont les plus exposés face aux glissements de terrain ; et les vulnérabilités y sont les plus élevées en particulier en Afrique (Petley, 2012; Susman et al., 2019; Ozturk et al., 2022). Dans le futur, la fréquence et l'ampleur des glissements de terrain dans ces régions sont appelées à augmenter suite aux changements d'utilisation du sol en lien avec la croissance démographique (Vanacker et al., 2003; DeFries et al., 2010; Guns and Vanacker, 2014; Lewis et al., 2015; Gill and Malamud, 2017; Ozturk et al., 2022), et suite aux conditions climatiques changeantes (épisodes plus intenses) (Gariano and Guzzetti, 2016; Sidle and Bogaard, 2016; Sekajugo et al., 2022). En plus, les fortes densités de population font que les populations locales cherchent des terres agricoles y compris sur des pentes instables, dont les glissements de terrain (Msilimba and Holmes, 2005; Nyssen et al. 2009; Eze et al. 2021). Il y a encore une méconnaissance sur les raisons de la présence des humains sur les glissements de terrain.

1.3 Facteurs de prédisposition des glissements de terrain

Les facteurs de prédisposition naturelles (topographie, lithologie, sols en place, etc.) et anthropiques (déforestation et d'autres activités humaines) des glissements de terrain sont connues (Sidle and Ochiai, 2006; Sidle and Bogaard, 2016; Gill and Malamud, 2017; Pham et al., 2020; Jones et al., 2021). Les glissements de terrain sont le plus souvent déclenchés par des pluies ou des tremblements de terre. Différents types de glissements de terrain peuvent se produire, chacun avec des caractéristiques et des facteurs de prédisposition différents, et avec des probabilités spatiales, temporelles et de taille différentes (Corominas et al., 2014). En plus, la transformation de l'environnement, liée aux pratiques agricoles et au développement des infrastructures, peut accélérer les instabilités suite à la modification topographique et aux constructions entraînant des quantités excessives d'infiltration d'eau à la base des déclenchements de glissements de terrain. Cependant, cette transformation de l'environnement est beaucoup moins clair que ce raisonnement assez stéréotypé suggère. Des recherches récentes suggèrent que trop souvent l'importance des facteurs naturels est négligée ; ce qui conduira inévitablement à la surestimation des effets nuisibles que les humains peuvent avoir sur leur environnement (Kiage, 2013; Zhao et al. 2016).

Les glissements de terrain affectent presque toutes les régions du monde mais peu d'études fournissent d'estimations sur les facteurs conduisant aux risques et aux vulnérabilités (Emberson et al., 2020). Ces études, très souvent menées sur des régions relativement petites (< 1000 km² ; e.g.: Reichenbach et al., 2018), se concentrent sur le cadre naturel des processus, et se basent sur des informations récoltées à partir d'imageries satellitaires, de photographies aériennes et des observations de terrain (Guzzetti et al., 2012; Kargel et al., 2016). Bien que l'utilisation de telles méthodes se justifie pour des études régionales, cela ne permet pas de cerner l'ensemble des complexités locales liées à l'utilisation du sol et à l'anthropisation (Depicker et al., 2021b; Dewitte et al., 2021). En effet, en raison des nombreux paramètres environnementaux (topographie, lithologie, changement de la couverture forestière, etc.) qui entrent en ligne de compte dans l'occurrence des différentes catégories de glissements de terrain, chaque région a ses propres spécificités, par exemple, sur les occupations du sol et leur mode de gestion. Seules des données récoltées sur le terrain permettent de cerner la problématique de gestion (durable ou pas) du territoire dans son entièreté et ainsi d'apporter des réponses claires aux décideurs. En effet, les observations du terrain et les enquêtes menées auprès des populations permettent de récolter les informations sur les subtilités des conditions de prédispositions (déforestation par exemple), des percusseurs du déclenchement, des dommages directs et indirects, des mesures d'atténuation, etc. Dans un environnement où les données de base sont rares, il y a lieu d'initier des approches multi-méthodes afin de collecter les données les plus complètes possibles sur les facteurs d'occurrence des différentes catégories de glissements de terrain inventoriés (Dewitte et al., 2021).

Dans un premier temps, pour comprendre le processus de glissements de terrain, il y a nécessité de la constitution d'un inventaire régional multitemporel détaillé des glissements de terrain couvrant plusieurs décennies (Guzzetti et al., 2012; Thiery et al., 2020). Une des approches de l'inventaire détaillé est la combinaison de l'utilisation de la télédétection et des enquêtes de terrain pour la validation de l'inventaire (e.g: Eeckhaut et al., 2007). De nouvelles méthodologies ont été proposées ces dernières années pour cartographier automatiquement les glissements de terrain en utilisant, par exemple, les données d'observation de la Terre et l'apprentissage automatique (par exemple, Guzzetti et al., 2012; Prakash et al., 2021). Cependant, ces approches automatiques ne fonctionnent bien qu'avec des glissements de terrain récents ayant une signature spectrale claire. En outre, elles ne sont pas toujours bien adaptées à une compréhension précise des processus (Jones et al., 2021) en particulier lorsque les paysages sont complexes et fortement influencés par les activités humaines (Jacobs et al., 2018). La nécessité d'une identification visuelle des glissements de terrain est encore plus importante lorsque les mouvements étudiés sont plus anciens et se sont produits à une période inconnue, bien avant la disponibilité des images satellitaires (Pánek et al., 2021). Les images © Google Earth, les ombres portées issues des images radar à haute résolution et les photographies aériennes historiques sont des sources de données de base pour repérer les instabilités gravitaires afin de les cartographier visuellement les glissements de terrain (Guzzetti et al., 2012; Corominas et al., 2014; Reichenbach et al., 2018; Mohammadi et al., 2018; Rabby and Li, 2019). Les enquêtes de terrain, sur différents environnements représentatifs de la zone à étudier, sont aussi importantes pour valider l'identification des glissements de terrain et évaluer la précision sur la catégorisation de ceux-ci (Guzzetti et al., 2012; Mohammadi et al., 2018; Rabby and Li, 2019). Aussi, les travaux de terrain permettent, grâce aux interviews auprès des populations, de recueillir les informations sur les conditions d'occurrence des glissements de terrain, notamment les précurseurs de l'évènement, les affectations du sol, les dommages, le mode de culture, etc.

En second lieu, il y a lieu d'évaluer l'importance des contributions de facteurs naturels et anthropiques dans l'occurrence des glissements de terrain. L'analyse de susceptibilité peut servir à mieux déterminer les contributions de chaque facteur de prédisposition afin de mieux connaitre les processus en place. Dans de nombreux cas, les modèles de susceptibilité aux glissements de terrain qui existent ne prennent pas en compte de manière approfondie les spécificités régionales et locales de facteurs d'occurrence des glissements de terrain. Ces modèles (Fig. 1.1) établis à l'échelle régionale (Depicker et al., 2020), continentale (Broeckx et al., 2018) ou globale (Stanley and Kirschbaum, 2017) ne tiennent pas en compte des considérations liées, par exemple, à l'âge des glissements de terrain et des facteurs environnementaux locaux supposés être à la base de leur occurrence. Ainsi, il est primordial de produire des modèles de susceptibilité qui différencient les processus des glissements de terrain et qui intègrent les facteurs de prédisposition réellement supposée être responsables de leurs occurrences.

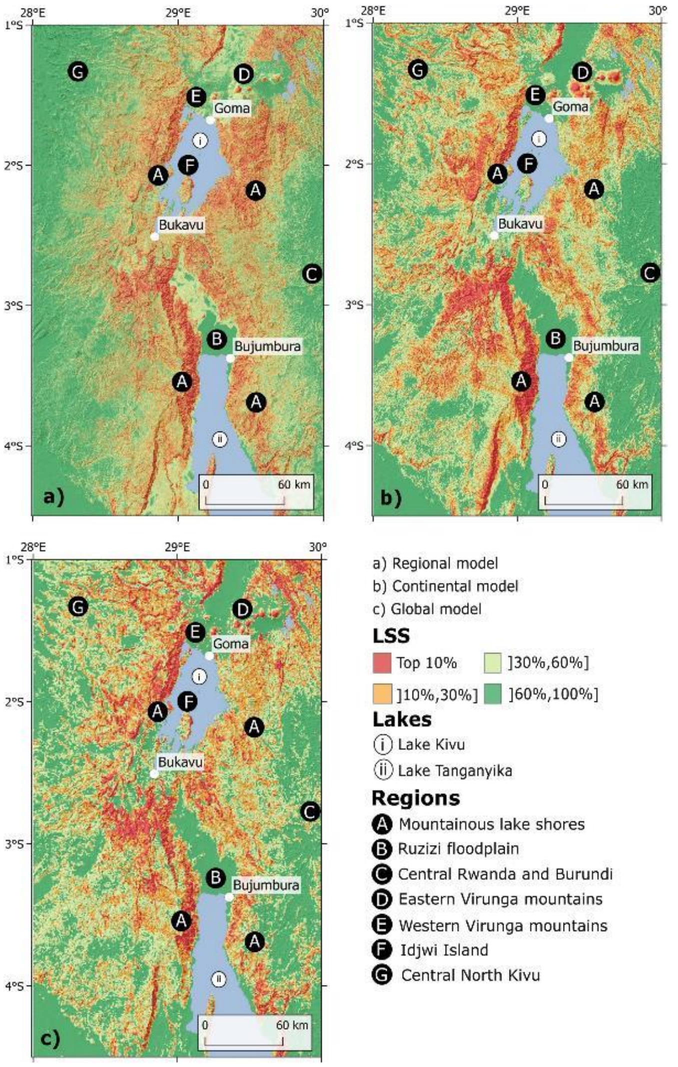


Figure 1. 1*: Susceptibilité normalisée aux glissements de terrain pour des modèles régionaux et mondiaux : (a) le modèle régional combiné (Depicker et al., 2020), (b) le modèle continental de Broeckx et al. (2018), et (c) le modèle mondial de Stanley and Kirschbaum (2017).*

1.4 Glissement de terrain et anthropisation

Les impacts négatifs (pertes en vies humaines et blessés, destruction d'infrastructures, délocalisation des populations impactées, etc.) des glissements de terrain sont bien connus à travers le monde. Cependant, dans un contexte de forte pression démographique, les zones instables, après que les glissements de terrain ont eu lieu, sont confrontées aux occupations du sol diversifiées (mise en valeur) (Walker and Shiels, 2013). Dans ces environnements anthropisés, il se pose aussi la question sur la manière avec laquelle se végétalisent les cicatrices des glissements de terrain et des zones impactées par les coulées de débris et les crues éclairs (Nakileza and Tushabe, 2018; Hu et al., 2018; Broeckx et al., 2019).

1.4.1 *Mise en valeur des glissements de terrain*

Dans les zones montagneuses, les glissements de terrain peuvent constituer des opportunités pour les populations vivant dans leurs environnements. Ils sont, en effet, à l'origine de conditions topographiques et d'humidité et de nature des sols différentes qui peuvent s'avérer favorables à une utilisation du sol adaptée (Walker and Shiels, 2013). Par exemple, une étude en Alaska a montré que la fertilité du sol est plus élevée dans la zone de dépôt de glissements de terrain (Adams and Sidle, 1987). Hewitt (2010) montre que le replat de grands glissements de terrain peut offrir une topographie favorable à l'implantation d'infrastructures, voire dans certains cas, de villages entiers dans des régions montagneuses. En plus de la fertilité potentielle des sols, les humains choisissent parfois de vivre sur des pentes instables parce que tout danger futur est compensé par l'immédiateté des bénéfices (Walker and Shiels, 2013). Les difficultés économiques, les fortes densités de population, la nécessité d'étendre l'agriculture à des terres marginales et l'ignorance des dangers potentiels peuvent également contraindre les humains à vivre sur des pentes instables (Walker and Shiels, 2013). A notre connaissance, la littérature ne renseigne pas, de manière explicite, sur la manière avec laquelle les populations des zones montagneuses tropicales vivent sur et exploitent les glissements de terrain et l'étendue de ces mises en valeur. C'est qui nous interroge aussi sur les facteurs naturels et anthropiques en place qui poussent les populations locales à exploiter les glissements de terrain. Par exemple, sur le Mont Elgon en Ouganda, l'étude menée sur la fertilité des sols, entre l'intérieur des glissements de terrain et les terres adjacentes, montre que les sols sont plus fertiles à l'intérieur des glissements de terrain anciens de plus de soixante ans ; mais moins fertiles pour l'intérieur de glissements de terrain que leurs versants adjacents (Van Eynde et al., 2017). Ainsi, il serait évident que certains facteurs environnementaux présents au sein des glissements de terrain seraient susceptibles d'induire des mises en valeur différenciées par rapport aux versants adjacents. On pourrait supposer que les bénéfices tirés de l'exploitation d'un glissement de terrain réduiraient la perception du risque.

1.4.2 Végétalisation des glissements de terrain superficiels

Les glissements de terrain superficiels déclenchés lors des événements majeurs tels que les pluies intenses entraînent des pertes de terre et emportent la végétation existante (Sidle and Bogaard, 2016; Adhikari and Hartemink, 2016; Pandey et al. 2022). Les cicatrices laissées par ces glissements de terrain sont des lieux de réactivation importante lorsque la végétation est dégradée (Pandey, 2017; Rengers et al., 2020). Suivant, les conditions climatiques locales, les glissements de terrain évoluent différemment (Fig. 1.2). Dans les régions à revenu élevé, lorsque les conditions matérielles le permettent, à court-terme, la réhabilitation des sites affectés passe par la plantation d'arbres adaptés, la stabilisation des pentes, la construction de structures de retenue des matériaux mobilisés (gabions, murs de terre…), l'interception des eaux de ruissellement par un système de drainage adapté et, si nécessaire, la fertilité du sol est améliorée par l'ajout d'engrais pour favoriser la végétalisation des glissements de terrain (Gray and Sotir, 1996 ; Bradshaw, 1997; Cornforth, 2005 ; Scotton and Andreatta, 2021). Au court du temps, les traces de ces glissements de terrain et les zones impactées finissent par disparaître naturellement et/ou des suites de la reforestation (Beguería, 2006). Et sans d'interventions d'ingénierie, les traces des glissements de terrain peuvent disparaître sur quelques années par suite des conditions humides qui favorisent la croissance rapide spontanée de la végétation ou par suite des nouvelles affectations de ces sols perturbés pour l'agriculture (Zimmermann and Elsenbeer, 2008; Nakileza and Tushabe, 2018; Broeckx et al., 2019; Sekajugo et al., 2022)

Les connaissances qui existent sur le processus du changement de la couverture végétale de glissements de terrain superficiels sont variées. Certaines analysent les effets des racines de la nouvelle végétation sur la stabilisation des pentes (Elias and Dias, 2009; Buma and Pawlik, 2021; Masi et al., 2021) ; d'autres études s'intéressent au suivi à long terme par des études basées sur des mesures de terrain afin d'évaluer la restauration du sol originel (Matsumoto et al. 1999; Burri et al. 2009). Ces études montrent que la végétation finit par se restaurer et effacer les traces des glissements de terrain superficiels. Très peu d'études se sont intéressées à la quantification du changement de la couverture végétale, sur le plan spatio-temporel, des zones impactées par les glissements de terrain à court-terme (Khan et al. 2013; Christmann and Menor, 2021; Saito et al. 2022). L'étude de Gao and Maro (2010) renseigne que, quelques années après le déclenchement des glissements de terrain, il est possible de détecter des changements de la couverture végétale qui se sont produits dans les zones touchées. Il peut arriver qu'on enregistre une forte diminution des cicatrices laissées par les glissements de terrain là où la végétation a connu une croissance importante (Khan et al., 2013). L'analyse, sur une courte période, du changement de la couverture végétale est donc nécessaire pour comprendre la dynamique de l'évolution du phénomène afin d'appréhender la temporalité de la végétalisation des cicatrices des glissements de terrain superficiels et d'analyser les facteurs environnementaux supposés contribuer ou non à cette disparition. Cette connaissance pourrait permettre de prévoir l'impact des glissements de terrain futurs qui entraineraient des pertes inattendues en vies humaines et en biens (Zhang et al., 2016).

En milieu tropical, il est souvent dit que les conditions climatiques plus humides qui y règnent peuvent favoriser la recolonisation rapide par la végétation (Walker et al., 1996). Dans ces régions, le manteau de régolithe est souvent épais, en raisons de l'altération de roche mère en place, pouvant permettre la repousse de la végétation (Beauvais et al., 2007). Mais, ce régolithe est plus sensible aux processus d'érosion, notamment les glissements de terrain superficiels, si le relief est abrupt (Beauvais et al., 2007). Cependant, il s'observe des spécificités suivant les conditions environnementales de chaque région (lithologie, topographie, couverture végétale, activités humaines, etc.) qui peuvent favoriser ou non la revégétalisation. Dans les régions d'Asie centrale, les contraintes socio-économiques font que la régénérescence de la végétation se fait, très souvent, de manière spontanée ou avec des espèces d'arbres peu adaptées (Hu et al., 2018). Dans ce cas, la végétalisation des glissements de terrain dépend principalement des conditions climatiques locales. En Malaisie, Razak et al. (2013) ont montré que la recolonisation de la végétation est rapide en milieu forestier des suites des conditions humides. Dans la région du Mont Elgon en Ouganda, la connaissance est encore limitée sur la végétalisation qui s'opère ; et elle se passe souvent d'une manière spontanée dans un contexte de forte pression anthropique (Nakileza and Tushabe, 2018; Broeckx et al., 2019). Il apparait qu'il y a encore un manque de connaissance sur la quantification de la cinématique du changement de la couverture végétale à court terme en milieu tropical où l'action anthropique est quasi permanente.

Le suivi du changement de la couverture végétale peut être étudiée en analysant une série d'images satellitaires sur une période donnée (Saito et al. 2022). Toutefois, en milieu tropical, les images satellitaires sont moins accessibles sur le plan temporel à cause de la couverture nuageuse fréquente ; celle-ci ne permettant pas d'acquérir une série temporelle la plus complète. Mais aussi, l'acquisition de ces images représente un coût financier important. D'où, la nécessité d'explorer le potentiel d'images en accès libre.

Les facteurs environnementaux en lien avec le changement de la couverture végétale sont aussi importants à examiner. En effet, la végétalisation pourrait dépendre de plusieurs facteurs environnementaux tels que topographiques, lithologiques ou de la couverture végétale à proximité (Yang et al., 2018; Yunus et al., 2020; Saito et al., 2022). Il est connu que la topographie en place, au sein d'un glissement de terrain, peut entrainer, si elle est abrupte, des éboulements ou des mouvements de substrat (blocs de pierre et/ou motte de terres) qui auront un rôle de frein par la mortalité de la végétation colonisatrice ; alors qu'une topographie moins accidentée favorisera la croissance des plantes (Dalling and Tanner, 1995). La nature du sol (texture, fertilité, humidité, etc.) en place influe la végétalisation car elle impacte sur la stabilisation des glissements de terrain superficiels par de multiples voies comme l'évapotranspiration, la structure des racines associées aux voies d'écoulement sous la surface (Sidle and Bogaard, 2016) et la disponibilité des éléments nutritifs et en eau (Dalling and Tanner, 1995). Les activités humaines (reboisement, culture sur brûlis, pâturage, constructions…) sont aussi à prendre compte dans la dynamique temporelle du changement de la couverture végétale des glissements de terrain. Pour mieux appréhender l'impact des activités humaines sur la végétalisation, les données recueillies sur le terrain sont essentielles.

1.5 Les objectifs de la recherche doctorale

L'objectif général de cette recherche est d'étudier les interactions entre les glissements de terrain et l'utilisation et la gestion du sol dans un contexte d'anthropisation d'un monde rural situé sur les versants du Rift à l'ouest du lac Kivu (RD Congo). La région des versants du Rift à l'ouest du lac Kivu est choisie pour les raisons suivantes : (1) la région montagneuse soumise à des fortes précipitations qui favorisent naturellement le déclenchement des nouveaux glissements de terrain chaque année; (2) le monde rural est fortement peuplé, avec une croissance importante de la population et des changements importants dans l'utilisation du sol (Depicker et al., 2021b). D'un point de vue local, les partenaires de recherches et les autres parties prenantes mentionnent une augmentation de la fréquence de ces événements et invoquent le changement climatique et/ou les changements environnementaux directs causés par l'homme comme principales causes. La relation causale entre les processus de glissements de terrain, le climat et l'utilisation du sol reste donc hypothétique dans notre zone d'étude. Le rapportage plus fréquent d'occurrence des nouveaux glissements de terrain est simplement attribué au changement des affectations du sol dû à l'augmentation de la densité de population dans la région. Dans premier temps, le défi fondamental consiste à mieux comprendre la part de facteurs de prédisposition naturels et anthropiques sur les occurrences des glissements de terrain. En second lieu, une meilleure connaissance de la façon dont l'activité de l'homme se déroule sur les glissements de terrain et les facteurs environnementaux favorables ou non. Enfin, l'évaluation de la temporalité de la végétalisation des cicatrices des récents glissements de terrain et des zones impactées est nécessaire dans ces environnements anthropisés.

Les objectifs spécifiques de la thèse tiennent compte du temps imparti et des coûts pour la récolte des données, combinant les approches de la télédétection et les enquêtes de terrain poussées, et leurs analyses. Les objectifs de l'étude consistent à :

- Analyser la distribution de glissements de terrain et identifier les facteurs de prédisposition qui les influencent à l'échelle régionale. Notre hypothèse principale se fonde sur le fait que la compréhension des processus de glissements de terrain nécessité d'élaborer un inventaire détaillé des différentes catégories de glissements de terrain. Les facteurs de prédisposition naturels et

anthropiques de ces glissements de terrain peuvent être identifiés à travers les analyses de susceptibilité.
- Identifier et examiner les logiques qui sous-tendent la mise en valeur des glissements de terrain dans un contexte de forte pression anthropique. A l'échelle locale, nous analysons les différences d'affectations du sol entre le glissement de terrain et les terres adjacentes. Les caractéristiques des glissements de terrain qui influent sur les mises en valeur des glissements de terrain sont aussi à identifier.
- Quantifier, à court-terme, la vitesse du changement de la couverture végétale post-déclenchement de récents glissements de terrain superficiel et de zones affectées par les coulées de débris-crues éclairs et analyser le rôle de facteurs environnementaux sur ce changement. La vitesse du changement de la couverture végétale est quantifiée à partir d'un événement pluvieux déclencheur de centaines de glissements de terrain.

1.6 Description de la zone d'étude

1.6.1 Situation géographique et caractéristiques biophysiques

La recherche doctorale a été conduite dans un environnement rural situé sur le Rift est africain à l'ouest du Lac Kivu entre les villes de Bukavu et Goma (Fig. 1.2). La zone d'étude couvre une superficie d'environ 5700 km². Sur le plan administratif, la zone englobe, en partie, les Provinces du Nord-Kivu et du Sud-Kivu à l'est de la RD Congo (Fig. 1.2). Les territoires administratifs, faisant partie de ces provinces, sont ceux de Walikale, Masisi dans le Nord-Kivu et de Kalehe, de Kabare et d'Idjwi dans le Sud-Kivu (Fig. 1.2a). Les territoires sont subdivisés administrativement en groupements au sein desquels sont présents de nombreux centres ruraux et villages.

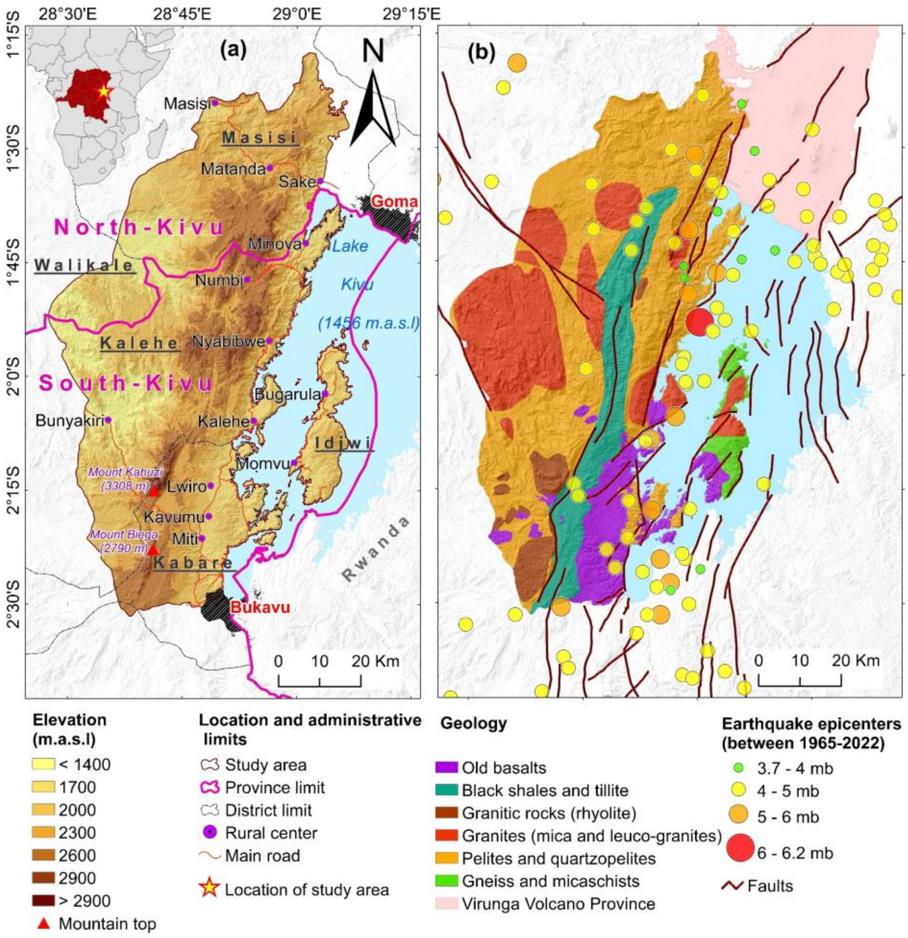


Figure 1.2: *Versants du Rift à l'ouest du Lac Kivu a) Relief et subdivision administrative et b) géologie et sismicité (Catalogue des tremblements de terrain de l'USGS « United States Geological Survey »: https://earthquake.usgs.gov/earthquakes/search/;consulté le 24/10/2022).*

Les versants du Rift à l'ouest du Lac Kivu constituent une région montagneuse appartenant à la dorsale des Monts Mitumba et faisant partie du bassin du fleuve Congo. Ils culminent, dans notre zone d'étude, au Mont Kahuzi (3308 m) et au Mont Biega (2790 m) (Fig. 1.2a). Six unités lithologiques, d'âges variés, sont présentes (voir Fig. 1.2b, source géologique : Laghmouch et al. 2018) et leurs âges et niveau d'altération (si disponible) sont présentés dans la Table 1-1. La région est l'une des plus actives sismiquement dans le système du Rift Ouest Africain car de nombreuses failles actives la traversent (Delvaux et al. 2017; Laghmouch et al. 2018). Au cours de ces deux dernières décennies, les enregistrements sur les tremblements de terre ont augmenté par suite de l'extension des réseaux des mesures interconnectés dans la cadre des partenariats avec plusieurs institutions sur le plan régional et international (RMCA, ECGS, ISC, OVG, CRSN Lwiro). En général, les magnitudes de ces tremblements de terrain sont généralement modérées (voir Fig. 1.4a : Catalogue des séismes des magnitudes supérieures à 3 mb entre 1965 – juin 2022 : https://earthquake.usgs.gov/earthquakes/search/; consulté le 08/08/2022). Et les dommages y sont moyemment sévères (Fig. 1.3bc). La sismicité régionale contribue aussi, à long terme, à la fracturation et affaiblissement des pentes (fatigue des matériaux due à des charges répétées de séismes même de faible magnitude) favorables au déclenchement des glissements de terrain (Delvaux et al. 2017; Depicker et al. 2021).

Table 1-1: *Unités lithostratigraphiques sur les versants du Rift à l'ouest du lac Kivu, présentées par ordre chronologique (Laghmouch et al., 2018; Depicker et al., 2020). La chronostratigraphie n'est valable que pour la zone d'étude.*

Age	**Chronostratigraphie**	**Lithostratigraphie**	**Unité lithologique dominante**	**Constitution lithologique principale et/ou niveau d'altération**
12-6 Ma	Neogene	Anciennes roches volcaniques	Vieux basaltes	Basalte très altéré, déposé il y a 11-4 Ma.
1000-540 Ma	Neoproterozoic	Itombwe	Schistes noirs, tillite, tillite silicifiée,	Faiblement métamorphisés.
		Complexe alcalines	Roches granitiques	Roches volcaniques intrusives (rhyolite) (820-720 Ma).
1600-1000 Ma	Mesoproterozoic	Granites	Granites	Deux micas et leuco-granites (1378-980 Ma).
		Kivu	Pélites, quartzopélites	Roches à différents degrés d'altération.

			et quartzites	Modérément métamorphisées.
2500-1600 Ma	Paleoproterozoic	Ruzizi et pré-Ruzizi	Gneiss et micaschistes	Sujets à l'altération chimique, et quartzites, résistants à l'altération. Fortement métamorphisés.

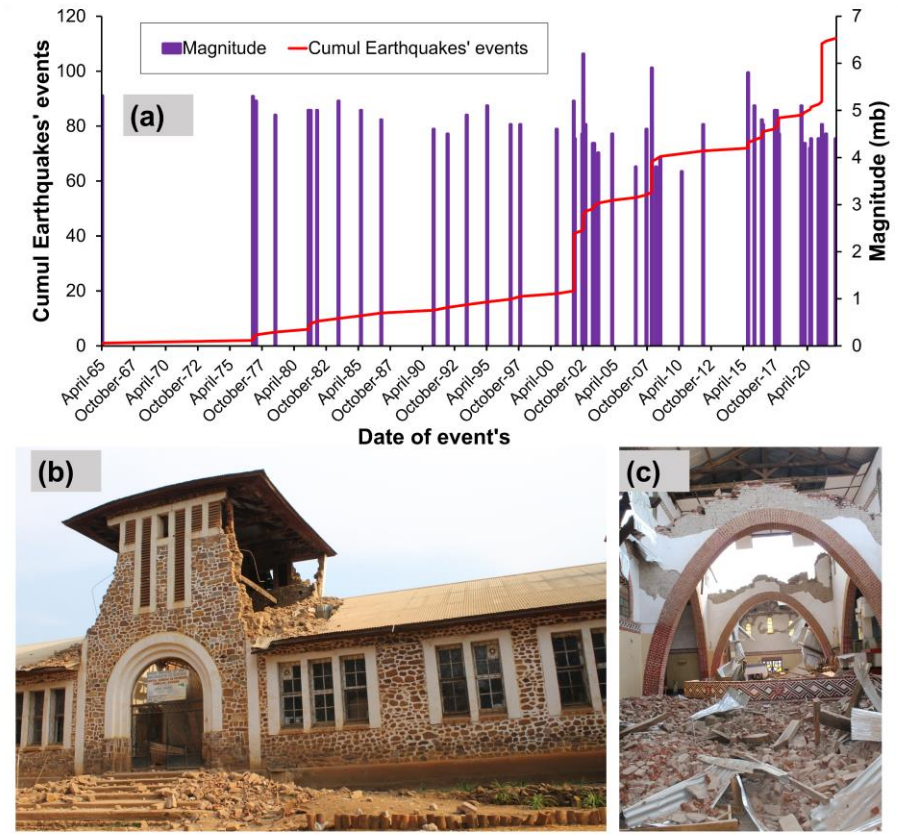


Figure 1.3 *: Activités sismiques dans la région du Rift Est-Africain. (a) Fréquence et magnitude des tremblements de terre dans la région ; (b) Eglise catholique Saint Lambert de Mwanda (2.221°S, 28.857°E) et (c) l'hôpital de la FOMULAC-Katana (2.234°S, 28.860°E) detruits en partie suite au tremblement de terre de 5.8 mb dans la nuit du 06 au 07 août 2015.*

La région jouit d'un climat tropical de savane/mousson tempéré par l'altitude (Peel et al., 2007). Les pluviométries mensuelles moyennes suivent les mêmes tendances pour l'ensemble de la zone d'étude (voir Fig. 1.5 ; Source : précipitations mensuelles entre janvier 2014 et septembre 2021 pour différents sites de la zone d'étude, https://developers.google.com/earth-engine/datasets/catalog/ NASA_ GPM_L3_IMERG_MONTHLY_V06 ; consulté le 07/07/2022). Les cycles des précipitations (Fig. 1.4) montrent des déficits pluviométriques autour de juillet (saison sèche) et des maxima en octobre (saison pluvieuse). La pluviométrie moyenne annuelle pour toute la zone d'étude est d'environ 1560 mm ; avec une moyenne des maxima de 1970 mm et une moyenne des minima de 1350 mm. Par ailleurs, les contrastes altitudinaux de cette région montagneuse créent une forte hétérogénéité des conditions climatiques locales. Les précipitations intenses sont reconnues comme étant à la base des récents déclenchements des glissements de terrain dans notre zone d'étude (Monsieurs et al., 2018b). Parfois, les conditions du déclenchement des glissements de terrain dépendent des conditions pluvieuses antécédentes sur plusieurs jours (Monsieurs et al., 2018b). Les températures moyennes entre les différents sites varient, selon l'altitude, entre 16 et 21°C (Données entre janvier 1981 et juin 2020: ERA5 Monthly Aggregates https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY, consulté le 24/10/2022).

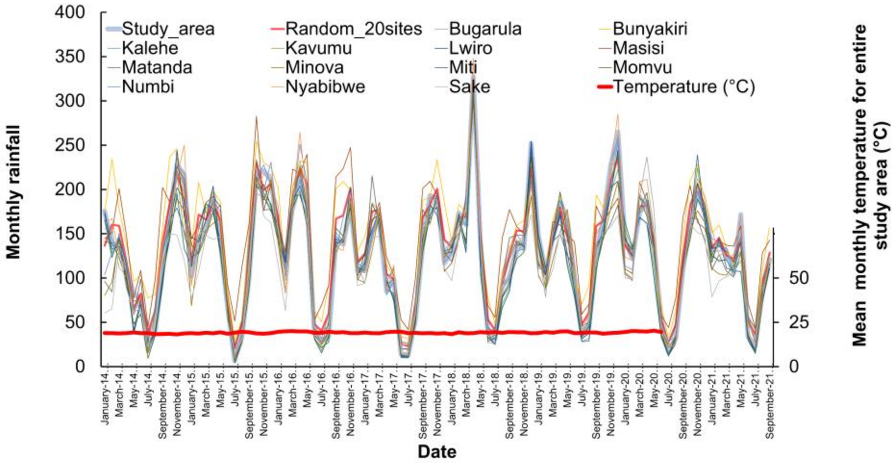


***Figure 1.4**: Régime pluviométrique et température moyenne mensuelle de la zone d'étude (les centres ruraux identifiés pour les mesures sont sur la Figure 1.2a) (Données satellitaire issu d'Integrated Multi-satellitE Retrievals for GPM (IMERG_V06), Huffman et al., 2019).*

La végétation naturelle est principalement une forêt montagnarde, encore préservée dans le parc national de Kahuzi-Biega (Imani et al., 2017) et qui, à ce jour, a le statut de patrimoine mondial en péril (UNESCO, 2021). Les conditions climatiques orographiques impactent sur la répartition du couvert végétal et les modes d'occupation du sol. Autrefois, d'est à l'ouest, entre le bord du lac (1456 m d'altitude) jusqu'à environ 1700 m d'altitude, une forêt mésophile dominait, mais la quasi-totalité a été convertie en terres agricoles (Lebrun 1960; Nzabandora 2016). Une zone de transition entre 1700 m et 1900 m où s'étendait un mélange d'espèces composées de futaie à sous-bois dense et des espèces mésophiles des zones inférieures (Nzabandora, 2016). Entre 1900 m et 2600 m subsiste encore une partie de la forêt ombrophile de montagne de *Podocarpus* constituée d'épiphytes; jusqu' 3200 m se trouvent des espèces montagnardes arbustives (Lebrun 1960; Nzabandora 2016). Plus à l'ouest entre 800m et 1800 m se trouvaient successivement des forêts sempervirentes de basse et moyenne altitude et la forêt dense submontagnarde. Dans cette zone de haute altitude, quelques reliques de forêt existent encore aujourd'hui malgré la conversion généralisée en terres cultivées et en pâturages. Entre les années 1955-58 (première source d'image issue des photographies aériennes panchromatiques) et 2016 (ESA, 2016), près de 50 % de la couverture forestière a disparu (Fig. 1.5). Ces dernières décennies, la déforestation et la perte de forêts ont été importantes (Basnet and Vodacek, 2015; Depicker et al., 2021a). Les coupes de bois se font soit d'une manière sélective (pour certains besoins spécifiques) ou par une coupe à blanc (pour les besoins agricoles, activités minières…) (Musumba Teso et al., 2019; Drake et al., 2019). Les observations du terrain montrent qu'après la déforestation, les terres sont souvent converties de façon permanente en terres agricoles (terres cultivées, prairies) ou en plantations d'arbres. Cependant, à certains endroits, la forêt se régénère naturellement (Masumbuko et al., 2012).

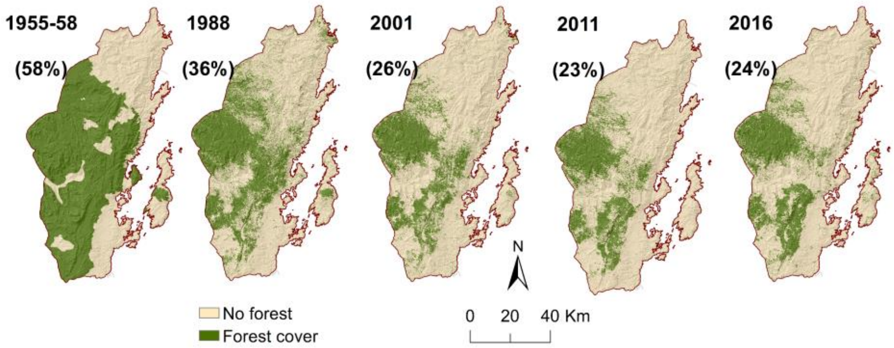


Figure 1.5: *Dynamique de la couverture forestière sur les soixante dernières années. Sources des images : 1955-58 (Photographies aériennes panchromatiques), 1988, 2001 et 2011 (Basnet and Vodacek, 2015) et 2016 (ESA, 2016).*

1.6.2 Aspects socio-économiques

La population de la zone d'étude est constituée d'une diversité des groupes ethniques. Chaque groupe ethnique a sa propre langue, bien que le Swahili est la langue communément parlée par toutes les communautés. Sur le plan démographique, c'est l'une des régions de la RD Congo la plus densement peuplée avec plus de 200 habitants/km² (Linard et al. 2012; Michellier et al. 2016; Trefon 2016). La taille des ménages arrive, en moyenne, à huit personnes (Dontsop-Nguezet et al., 2016; Ciza et al., 2022).

L'économie est essentiellement basée sur les cultures de subsistance (manioc, bananier, haricot, maïs, patate douce, colocaze, sorgho, divers légumes…), les cultures de rente (café, thé et quinquina), l'élevage (bovin, caprin, porcin, volailles…), la pêche artisanale dans le lac Kivu et l'exploitation minière artisanale. Les contraintes sécuritaires et les limites d'accès aux infrastructures de base freinent cependant le développement des activités socio-économiques des populations locales et les rendent aussi plus vulnérables aux aléas naturels. La taille moyenne d'une exploitation familiale varie entre 0.1 et 1 hectare (Ndjadi et al., 2020). La main d'œuvre pour les travaux en champ est essentiellement familiale utilisant des outils simples (houe, machette,…) ; et le système de métayage est bien présent. Les pratiques culturales sont essentiellement tributaires des saisons pluvieuses. Deux saisons agricoles sont en cours dans la région, à savoir la 'saison A' de Septembre jusqu'à Janvier et 'saison B' de Février jusqu'à Mai (Mwanjalolo Jackson-Gilbert et al. 2015; Karamage et al. 2016; Heri-Kazi and Bielders 2021). La pression foncière pousse les populations locales à exploiter des terres marginales, comme celles affectées par les glissements de terrain (Fig. 1.6). La diversité des paysages des versants montagneux, et la biodiversité qui s'y trouve, font de cette partie du Rift l'une des plus touristiques du pays. C'est notamment le cas du parc national de Kahuzi-Biega qui habrite des espèces animales protégées comme les gorilles de montagne (*Gorilla gorilla beringei,* e.g. Yamagiwa et al. (1993)).

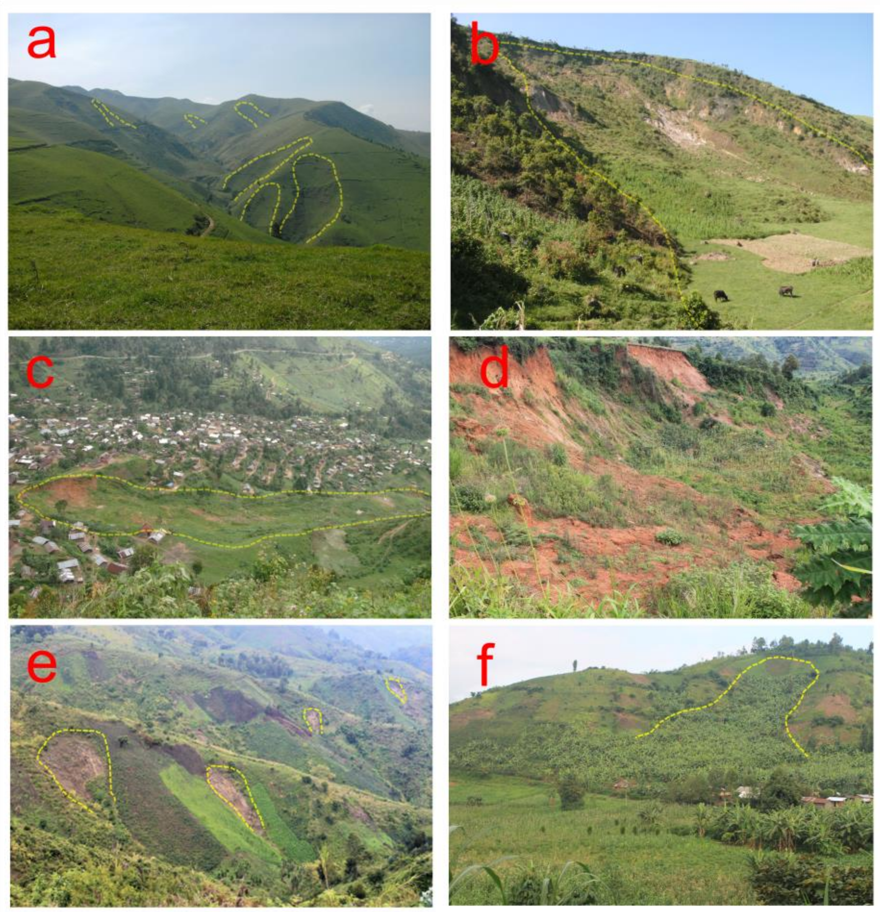


Figure 1. 6: *Utilisation des terres dans les environnements affectés par les glissements de terrain (ces derniers sont délimités, si nécessaire, par des lignes en pointillés jaune). a) Pâturage aménagé sur les versants abrupts de Masisi où de nombreux glissements de terrain anciens sont présents (1.523°S, 28.989°E) ; b) cultures vivrières et pâturages sur un glissement de terrain profond récent à Mushaki (1.521°S; 28.975°E) ; c) Centre rural minier de Nyabibwe affecté par le glissement de terrain profond récent (1.922°S, 28.934°E) ; d) cultures de subsistance dans un glissement de terrain pronfond récent au nord de l'île d'Idjwi (1.989°S ; 29.071°E) ; e) cultures de subsistance près de glissements de terrain superficiels récents (déclenché en octobre 2014) sur les pentes fortes de Kalehe ; f) bananeraies dans un glissement de terrain profond ancien à Minova (1.717°S ; 28.992°E).*

1.6.3 Aperçu des connaissances sur les glissements de terrain dans notre zone d'étude

La recherche doctorale se concentre sur une zone où les processus de surface comme les glissements de terrain sont très actifs (Moeyersons et al., 2010; Maki Mateso and Dewitte, 2014; Depicker et al., 2020; Dewitte et al., 2021). Depuis le début des années 2000, un meilleur enregistrement d'événements de déclenchement de nouveaux glissements de terrain permettent d'avoir plus d'informations sur les dommages directs qui s'ensuivent (voir Fig. 1.7 de Monsieurs et al. 2018a). Il est souvent suggéré que cela est dû à la dégradation de l'environnement provoquée par l'homme: par exemple, l'enlèvement et/ou la réduction de la couverture arborescente rend les pentes plus sensibles aux glissements de terrain (Dewitte et al., 2021). En effet, le dépérissement des racines des arbres réduit la résistance au cisaillement du sol.

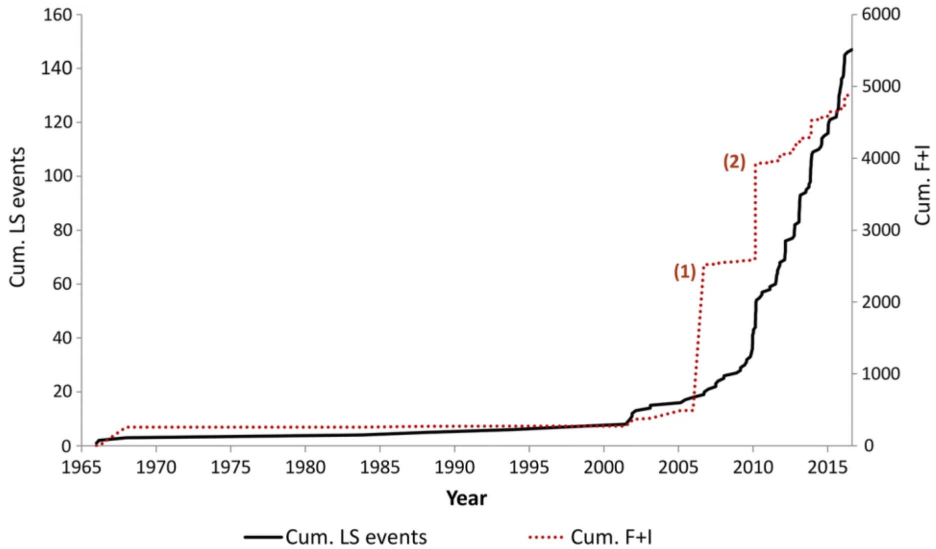


Figure 1. 7: *Nombre cumulé d'événements de glissement de terrain signalés (Cum. LS events) et leur somme cumulée respective de morts et de blessés (Cum. F+I) dans la branche occidentale du Rift est-africain (~200 000 km²). Deux événements de glissement de terrain à fort impact sont mis en évidence : (1) le 28 novembre 2006 :*

2024 victimes à Kigali, Rwanda ; (2) le 15 mai 2010 : 1297 victimes au Nord-Kivu, RD Congo (see Monsieurs et al., 2018a).

1.7 Structure de la thèse

L'étude procède par à une analyse de l'échelle régionale vers l'échelle locale. A l'échelle régionale, sur les versants du Rift à l'ouest du Lac Kivu, de nombreux glissements de terrain sont identifiés dans le paysage. Bien qu'il soit clair que certains d'entre eux sont plutôt anciens et exclusivement liés à des facteurs naturels, de dizaines voire de centaines des nouveaux glissements de terrain se produisent chaque année, parfois avec des impacts directs dramatiques (décès, blessés, disparus, destruction d'infrastructures, etc.). A partir des résultats à l'échelle régionale, une zone cible, à l'échelle locale, a été choisie pour mieux comprendre la complexité de la mise en valeur des glissements de terrain et du changement de la couverture végétale des glissements de terrain post évènement. Les informations à l'échelle locale vont servir à la compréhension sur la mise en valeur des glissements de terrain et de la vitesse du changement de la couverture végétale au sein des glissements de terrain déclenchés lors des événements pluvieux. Hormi, l'introduction générale et la conclusion générale, le travail est structuré en trois principaux chapitres dont les objectifs spécifiques se présentent comme suit.

Chapter 2 : Characteristics and causes of natural and human-induced landslides in a tropical mountainous region: the Rift flanks west of Lake Kivu

Chapitre 2 : Caractéristiques et causes des glissements de terrain naturels et anthropiques dans une région de montagne tropicale : les versants du Rift à l'ouest du lac Kivu (RD Congo)

L'étude réalisée à l'échelle régionale a consisté à la collecte des données, grâce à l'utilisation des diverses sources (images satellites, photographies aériennes, témoignages et observationsde terrain) pour : (1) inventorier en détail les glissements de terrain en récoltant des informations liées à leur profondeur, leur âge, le type de mouvement en place, etc.; (2) analyser la distribution des tailles des glissements de terrain selon l'environnement; (3) analyser les facteurs de prédisposition des différentes catégories de glissements de terrain en distinguant ceux qui sont naturels et ceux liés à des facteurs anthropiques.

Les analyses régionales permettent de cibler une région où des études, à l'échelle locale, sont menées sur les utilisations des terres et le changement de la couverture végétale après les occurrences des glissements de terrain. Pour les utilisations des terres, le choix est guidé suivant que la région a une forte densité de distribution des différents types de glissements de terrain et une forte anthropisation. Le changement de la couverture végétale, sur quelques années, est analysée sur un évenement majeur déclencheur des glissements de terrain et des crues éclaires dans un paysage influencé par l'homme.

Chapter 3 : Living on landslides: land use on unstable slopes in a rural environment west of Lake Kivu (DR Congo)

Chapitre 3 : Vivre sur les glissements de terrain : utilisation des terres sur des pentes instables dans un environnement rural sur les versants du Rift à l'ouest du lac Kivu (RD Congo)

L'étude a été menée à l'échelle locale, en comparant les affectations du sol de l'intérieur de glissements de terrain par rapport aux versants adjacents, en combinant les enquêtes de terrain et les analyses spatiales. Cela a permis de: (1) évaluer la perception du risque des exploitants suivant les caractéristiques des glissements de terrain, (2) évaluer si les caractéristiques des glissements de terrain conditionnent des mises en valeur différenciées et, plus largement, s'ils conditionnent la valeur des terres dans les glissements de terrain et le degré de satisfaction à exploiter ces glissements de terrain, (3) déterminer l'étendue et les modes de mise en valeur des glissements de terrain.

Les utilisations de terres au sein des glissements de terrain permettent d'identifier les implications anthropiques sur le changement de la couverture végétale des zones affectées par les glissements de terrain. Le rôle anthropique est analysé sur le changement spatio-temporel de la couverture végétale.

Chapter 4: The disappearance of a disaster: vegetation cover change following a landslide-flash flood compound event in a human-influenced landscape of DR Congo

Chapitre 4 : La disparition d'une catastrophe : le changement de la couverture végétale après un évènement majeur déclencheur des glissements de terrain et des crues éclaires dans un paysage influencé par l'homme en RD Congo

A l'échelle du glissement de terrain par rapport au versant adjacent, le suivi du changement de la couverture végétale de glissements de terrain superficiels et des zones affectées par le passage des coulées de débris a été quantifiée, sur une courte période, en termes de : (1) évaluer les tendances générales du changement de la couverture végétale à partir d'une série temporelle d'images Pléiades et Sentinel-2 desquelles ont été dérivées le NDVI relatif; (2) examiner les facteurs environnementaux et anthropiques qui impactent sur le point de départ et la vitesse du changement de la couverture végétale des différentes zones affectées par les glissements de terrain superficiels.

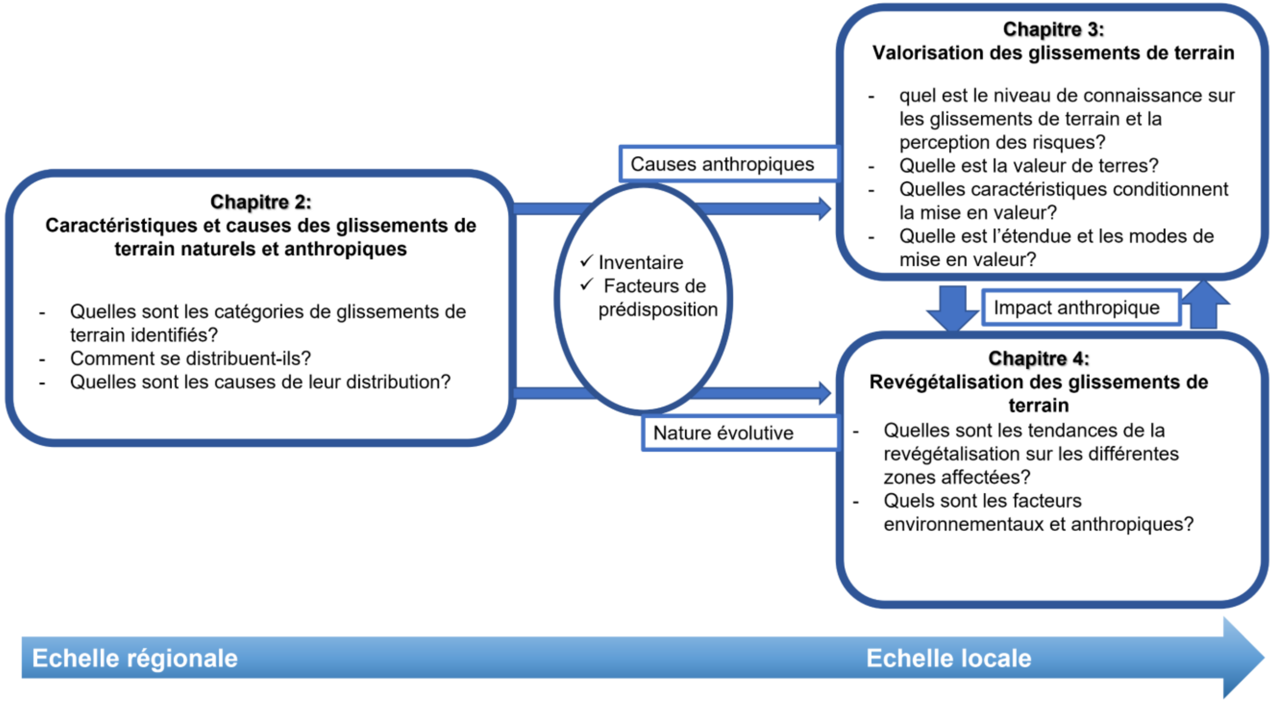


Figure 1.8: *Principaux cheminements de la thèse : les échelles spatiales, les principales questions et les interactions entre les différents chapitres.*

Chapter 2

Characteristics and causes of natural and human-induced landslides in a tropical mountainous region: the rift flanks west of Lake Kivu (DR Congo)

"we have entered the Anthropocene, a new geological epoch defined by humanity's influence on the global environment."

Daniel C Esty

This Chapter has been published as:

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2.1 Abstract

Tropical mountainous regions are often identified as landslide hotspots with growing population pressure. Anthropogenic factors are assumed to play a role in the occurrence of landslides in these densely populated regions, yet the relative importance of these human-induced factors remains poorly documented. In this work, we aim to explore the impact of forest cover dynamics, roads and mining activities on the characteristics and causes of landslides in the rift flanks west of Lake Kivu in the Democratic Republic of the Congo (DR Congo). To do so, we compile a comprehensive multi-temporal inventory of 2730 landslides. The landslides are of different types and are grouped into five categories that are adapted to study the impact of human activities on slope stability: old (pre-1950s) and recent (post-1950s) deep-seated landslides, shallow landslides, landslide associated with mining and landslides associated with road construction. We analyse the landslides according to this classification protocol via frequency-area statistics, frequency ratio distribution and logistic regression susceptibility assessment. We find that natural factors contributing to the cause of recent and old deep-seated landslides were either different or changed over time. Under similar topographic conditions, shallow landslides are more frequent, but of a smaller size, in areas where deforestation has occurred since the 1950s. We attribute this size reduction to the decrease in regolith cohesion due to forest loss, which allows for a smaller minimum critical area for landsliding. In areas that were already deforested in the 1950s, shallow landslides are less frequent, larger and occur on less steep slopes. This suggests a combined role between regolith availability and soil management practices that influence erosion and water infiltration. Mining activities increase the odds of landsliding. Landslides associated with mining and roads are larger than shallow landslides but smaller than the recent deep-seated instabilities, and they are controlled by environmental factors that are not present under natural conditions. Our analysis demonstrates the role of human activities on the occurrence of landslides in the Lake Kivu

region. Overall, it highlights the need to consider this context when studying hillslope instability characteristics and distribution patterns in regions under anthropogenic pressure. Our work also highlights the importance of considering the timing of using landslide classification criteria adapted to the context of the Anthropocene.

Keywords: landslide categories, multi-temporal inventory, historical deforestation, mining and roads landslides, susceptibility assessment, landslide area distribution, Africa

2.2 Introduction

Tropical mountainous regions are often identified as landslide hotspots with particularly vulnerable populations (Vanacker et al., 2003; Broeckx et al., 2018; Froude and Petley, 2018; Emberson et al., 2020). Nevertheless, the current knowledge on landslide processes in these regions remains commonly limited as it is mostly derived from susceptibility models made at continental or global levels (Stanley and Kirschbaum, 2017; Broeckx et al., 2018). Because they are not based on detailed local inventories, such models do not allow for properly considering region-specific characteristics and causes of landslides (Depicker et al., 2020).

The growing demographic pressure and widespread land use and land cover (LULC) changes are expected to increase the frequency and impacts of landslides in tropical mountainous regions, especially in rural environments (Vanacker et al., 2003; Sidle et al., 2006; DeFries et al., 2010; Mugagga et al., 2012; Guns and Vanacker, 2014; Froude and Petley, 2018; Depicker et al., 2021a; Muñoz-Torrero Manchado et al., 2021). Deforestation and the associated loss of tree roots usually lower the slope stability by decreasing the effective regolith cohesion and altering surface and subsurface water drainage patterns, whose effects are particularly pronounced on the occurrence of shallow landslides (Sidle and Bogaard, 2016). Mining, quarrying and road construction alter the environment and commonly increase landslide occurrence (e.g. Sidle et al., 2006; Brenning et al., 2015; Arca et al., 2018; McAdoo et al., 2018; Vuillez et al., 2018; Muñoz-Torrero Manchado et al., 2021;Tanyaş et al., 2022). However, the impact of these anthropogenic factors on landslide processes (e.g. types, size, dynamics) depends on their timing and their legacy effect. It also depends on other environmental conditions such as slope angle and lithology (Depicker et al., 2021a). Developing further our understanding of landslides and their natural and human-induced causes is therefore needed, especially in regions such as the tropics where the dearth of data is commonplace (Dewitte et al., 2022).

To achieve this, a detailed multi-temporal regional landslide inventory spanning several decades is essential (Guzzetti et al., 2012). New methodologies have been proposed in the past years to automatically map landslides with the use of, for example, earth observation data and machine learning (e.g.Prakash et al. 2021). However, such automotic approaches only perform well with recent landslides with a clear spectral signature. Futhermore, they are not always well adapted to an accurate understanding of the processes (Jones et al., 2021), especially when the landscapes are complex and highly influenced by human activities (Jacobs et al., 2018). The need for a visual identification of landslides is even more important when the movements that are studied are older and have occurred at an unknown period of time, much before the availability of sattelite images (Pánek et al., 2021).

Historical aerial photographs offer the best opportunity at the regional level to work across several decades, not only to compile a landslide inventory but also to reconstruct LULC changes (Glade, 2003; Guns and Vanacker, 2014; Shu et al., 2019). It is complementary to very high-spatial-resolution satellite images such as those available on Google Earth (Fisher et al., 2012), which are widely used in the identification of landslides in many environments (e.g. Broeckx et al., 2018; Pánek et al., 2021). Fieldwork is also essential in order to validate observations made from the different image sources, to discriminate between deep-seated and shallow processes, or to confirm depth estimates (Dewitte et al., 2021). Field surveys also help to understand the role of human activities on slope dynamics (Dewitte et al., 2021). Overall, sufficiently long and precise multi-decadal records of landslide activity, types and LULC are rare (e.g. Glade, 2003; Guns and Vanacker, 2014; Shu et al., 2019).

The aim of this work is to explore the role played by natural and human factors on the occurrence of landslides in a rural tropical mountainous region under high anthropogenic pressure. More specifically, we are interested in the rift flanks west of Lake Kivu, a region in the DR Congo where recent studies have shown that landslides are frequent and that recent deforestation has impacted the occurrence of shallow landslides (Maki Mateso and Dewitte, 2014). We aim to (1) further develop the existing landslide dataset and compile a comprehensive multi-temporal regional landslide inventory spanning several decades; (2) describe the general characteristics of the landslides; and (3) analyse their causes according to different controlling factors, with special attention to multi-decadal forest cover dynamics. Historical aerial photographs and field surveys are key sources of information in this study.

2.3 Environmental settings and current knowledge of the landslide processes

The study is conducted in the rift flanks west of Lake Kivu in the DR Congo (Fig. 2.1a). It is one of the most seismic regions of the African continent, crossed by active faults and composed of six main rock types of varying age (Fig. 2.1b) (Delvaux et al., 2017; Laghmouch et al., 2018). A significant portion of the study area is made of lithologies from the Archean, the Mesoproterozoic and the Neoproterozoic, with various degrees of chemical weathering and fracturing (Kampunzu et al., 1998). Lastly formed rocks are the old Neogene basalts, highly weathered, that were deposited between 11-4 Ma. The presence of mineral resources (gold and 3T minerals - tin, tantalum and tungsten) favours the proliferation of, often illegal, artisanal and small-scale mining and quarrying (Van Acker, 2005; Geenen, 2012; Bashwira et al., 2014). Industrial mining is not present in the region and there is no new road construction associated with it (Bashwira et al., 2014).

The region has a tropical savannah/monsoon climate tempered by its elevation (Peel et al., 2007). The natural vegetation is mainly montane forest, still preserved in the Kahuzi-Biega National Park (Imani et al., 2017). Between the 17th and 18th centuries, the first intense human disturbance occurred as a result of deforestation (Nzabandora and Roche, 2015). The roads built during the late 19th and first half of the 20th centuries played a key role in further expanding the intense human distrurbance (Aleman et al., 2018). There has been significant deforestation and forest loss in recent decades as well (Basnet and Vodacek, 2015; Depicker et al., 2021a,b). Selective logging is done for energy needs, house construction, furniture production and dugout canoes. Clear-cutting, mostly small-scale, is associated with agriculture, mining and quarrying activities, and road construction (Musumba Teso et al., 2019; Drake et al., 2019). After deforestation, the land is often permanently converted to agricultural land (cropland, grassland) or tree plantations (Depicker et al., 2021b). In some places, however, natural regeneration of the forest takes place (Masumbuko et al., 2012).

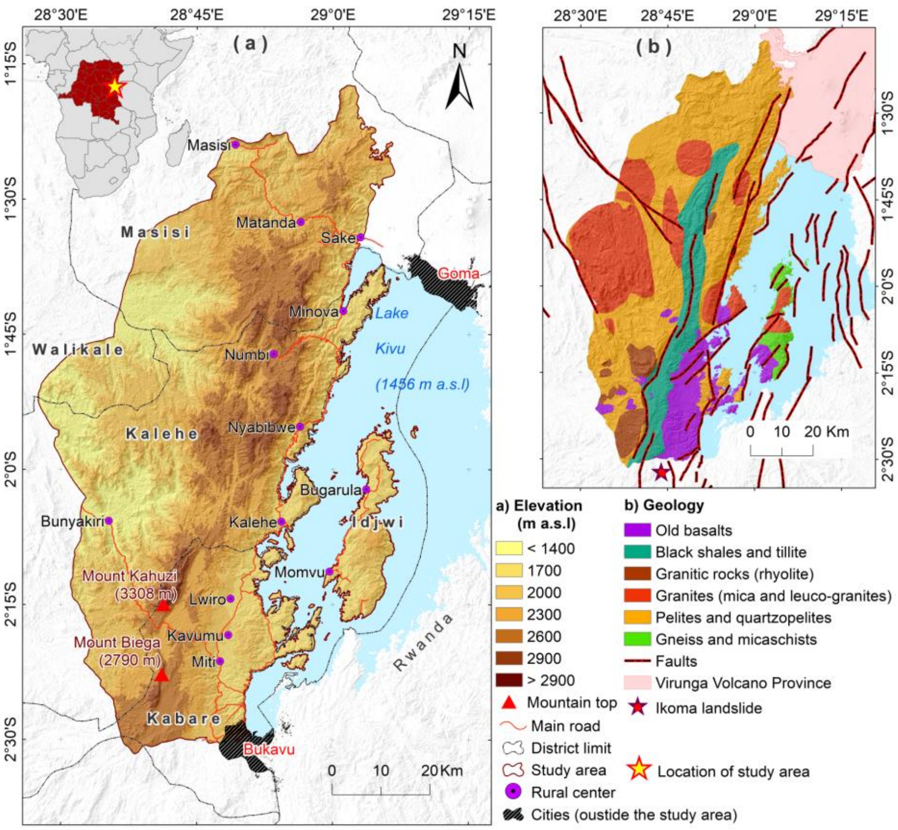


Figure 2. 1: *(a) Relief and (b) geology of the study area. The study area covers the districts of Kabare, Kalehe, Walikale, Masisi and Idjwi. Topography is derived from*

the Shuttle Radar Topography Mission (SRTM) 1 arc second product (https://lpdaac.usgs.gov/products/srtmgl1v003/). Lithology and fault maps are from Laghmouch et al. (2018).

The study area (~ 5,700 km²) is one of the most densely populated regions of the DR Congo with more than 200 inhabitants km^{-2} living mainly from agriculture, mining and quarrying activities (Linard et al., 2012; Michellier et al., 2016; Trefon, 2016). This region plays a key role in the supply of food and charcoal to the smaller rural centres and to the cities of Goma and Bukavu. Over the last decades, the population in both cities increased from a few tens of thousands to more than 1 million inhabitants (Michellier et al., 2016). The population growth in the study area was partly caused by the influx of Rwandan refugees in 1994-1995, as well as the growing artisanal mining industry that offers job opportunities (Bashwira et al., 2014; Van Acker, 2005; Butsic et al., 2015;). The road network is relatively limited (Fig. 1a). Most roads are dirt roads and are poorly maintained, and there are no built-up walls (concrete, gabions) to stabilise the cut slopes.

A first preliminary inventory of a few hundred landslides showed that the landslide processes are diverse and that their impacts on rural development can be high (Maki Mateso and Dewitte, 2014). The inventory over the North Tanganyika-Kivu rift region (hereafter called NTK rift) of which our study area is a subregion was further expanded by Depicker et al. (2020) through the use of Google Earth imagery. This inventory consisted of shallow and deep-seated landslides and did not distinguish for landslide susceptibility type. Depicker et al. (2020) showed that, in addition to slope angle, land cover is a key landslide predictor in the NTK rift region. A more detailed investigation of the annual evolution of the forest cover over the last 20 years showed that deforestation increases the erosion due to the occurrence of new shallow landslide erosion tow to eight times during a period of approximately 15 years before it eventually falls back to a level similar to forest conditions (Depicker et al., 2021a). A catalogue of > 150 accurately dated landslide events, i.e. landslides that can be clearly associated with a common well-defined triggering rainfall event over the same area, was compiled for the NTK rift for the last 2 decades. It allowed for demonstrating the role of rainfall seasonality on the occurrence of new landslides (Monsieurs et al., 2018b; Dewitte et al., 2021). Some landslide events consist of clusters of several hundred of shallow slope failures. The spatial extent of such clustered events can be larger than 10 km². A few events like these occur during each wet season (Depicker et al., 2020; Dewitte et al., 2021). They are commonly associated with particularly intense convective rainfall (Monsieurs et al., 2018a). None of the dated landslide events were triggered by earthquakes (Dewitte et al., 2021). This does not discard the role of earthquakes in triggering landslides in the region, but instead reminds us that the return period of earthquakes with a magnitude large enough to trigger slope instabilities can be much longer than a few decades (Delvaux et al., 2017). Their potential impact, rather localised compared to that of climatic drivers, can be inexistent during a narrow time window of observation (Dewitte et al., 2021; Depicker et al., 2021b).

Landslides can also occur due to rock weathering and regolith formation (Dille et al., 2019). In other words, the long-term evolution of these preconditioning drivers alone can explain that a slope can also fail without any apparent trigger. This implies that the many landslides that occur in isolation of other events must be interpreted with care in terms of origin. For these features, it is not clear from a visual analysis of the satellite images whether they can be directly linked to a direct trigger. In addition, many landslides occur in isolation along roads (Dewitte et al., 2021). Some of the larger, historical landslides (i.e. landslides that do not appear active in our oldest source of information) are probably more than 10,000 years ago (Dewitte et al., 2021).

2.4 Material and methods

2.4.1 *Landslide inventory*

The landslide inventory is a significant update of the inventory compiled by Depicker et al., (2020) who used only Google Earth imagery for mapping the features whatever their type; age; and rainfall, seismic or non-triggered origin as explained in Section 2.2. Since the focus of Depicker et al., (2020) was to study landslides over a much larger region than the one of the present research, their inventory was performed not only during a limited search time on our study area but also without a field survey. Moreover, in our research, we differentiated between types and timing of landsliding as these are key elements to consider to differentiate between natural and human-induced landslides (Hungr et al., 2014; Slide and Bogaard, 2016). In order to propose a landslide classification system adapted to our research objective, we strongly relied on three image products.

- A careful and detailed 3D (elevation exaggeration of 1) visual interpretation of Google Earth images from 2005 to 2019 provides complete coverage of the region at very high spatial resolution (~0.5 m), often multi-temporal.
- The interpretation of two hillshade images is derived from a TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) digital elevation model (DEM) provided at 5 m resolution and covering a large part of the region (see Albino et al., 2015, and Dewitte et al., 2021 for technical explanation on the production of the DEM). Despite some artefacts present in the DEM (Albino et al., 2015), this resolution allows for visually indentifying geomorphological features relevant for characterising landslide processes (Dewitte et al., 2021). The hillshade images were produced with a sun elevation angle of 30° and sun azimuth angle of 315° and 45°.

- The stereoscopic analysis of historical panchromatic photographs is acquired during the 1955-1958 period at a ~1/50,000 scale (i.e. about 1 m spatial resolution on the ground). The photographs are conserved at the Royal Museum for Central Africa (RMCA, Belgium).

The historical aerial photographs allowed for differentiating between old deep-seated landslides (i.e. landslides with an unknown time of origin and already present on the photographs) and recent deep-seated landslides that have occurred during the last 60 years (i.e. after the acquisition of the photographs). The aerial photographs were not used for mapping shallow landslides since this inventory would be biased. Indeed, the spatial resolution of the photographs is twice lower than that of the images in Google Earth. Furthermore, the photographs provide a single temporal cover, whereas the multi-temporal Google Earth images are composites over 13 years, i.e. the age difference between the oldest and youngest image. (e.g. Minova, Kalehe, Matanda in Fig. 2.1:).

The estimation of the depth of a landslide is important when the role of LULC is to be considered; shallow landslides are much more sensitive to changes in vegetation characteristics than deep-seated landslides (Sidle and Bogaard, 2016). In the literature, a landslide is usually defined as shallow when the depth of its surface of rupture ranges between 2 and 5 m (Keefer, 1984; Bennett et al., 2016; Sidle and Bogaard, 2016). Here, landslides with a depth of < 5 m were considered shallow. This criterion is based on the numerous field observations in the region that show that regolith can easily develop over a depth of several metres and that trees often show deep rooting systems. Following the approach of Depicker et al. (2020) and Dewitte et al., (2021), the distinction between deep-seated and shallow landslides was made by visually estimating the relative landslide depth from Google Earth and the 5 m resolution TanDEM-X hillshade images. Extensive in situ field observations of several hundred recent landslides where then carried out to validate the assessment. The landslides occurring in mining and quarrying sites were all classified as mining landslides. Specific attention was also given to the landslides occurring along roads. Mining and road landslides are assumed to be related to important anthropogenic changes in the topography. Once they have occurred, field observations show that these landslides are commonly reworked and often further excavated. Therefore, for these two types of landslides, their depth was not assessed.

Six field surveys were conducted over the period 2016 to 2019 to validate the landslide inventory and get extra information on the landslide timing and their causes and triggers. Additional landslides identified only in the field were not considered in the analyses as they would bias the regional landslide distribution. The work was carried out by selecting representative areas with various types of landslides and areas with feweror no landslides. These areas, which cover a total of ~20% of the region, were selected based on different landscape characteristics (lithology, slope, LULC) while taking into account accessibility and safety issues that prevent access to many places (Jaillon, 2020). We also used information from media and grey literature (student theses, field reports from local research, publications from academic institutions and the civil protection authorities).

The frequency of landslide surface area distributions were analysed to check the completeness of the inventory and also enable comparison with other inventories in different environments. If the frequency-area density can be properly fitted to an inverse gamma (Γ) distribution, it is considered representative of the study area (Malamud et al., 2004). A bad fit could suggest that the inventory is biased and/or incomplete. Indeed, the use of several data sources in the inventory could bias the distribution of landslides, especially bearing in mind the limitations related to the interpretation of satellite images (Guzzetti et al., 2012). We performed this analysis separately for five categories of the inventory considered together or in isolation: all landslides, old and recent deep-seated landslides, shallow landslides, mining landslides, and road landslides (see Section 2.3.1). The analysis of the frequency-area distributions for the different shallow landslide populations defined according to the LULC and its dynamics was also used to infer about differences in environmental characteristics and slope failure mechanisms (Malamud et al., 2004; Van Den Eeckhaut et al., 2007; Guns and Vanacker, 2014; Tanyaş et al., 2018). Box-plots complemented the shallow landslide area analysis.

The extent of the study area is relatively small when considering regional climatic characteristics, and the time window of the shallow landslide inventory built from Google Earth imagery is limited to a few years. Therefore, the location and spatial properties (areal extent, number of occurrences) of a rainfall-triggered landslide event forming a cluster of slope failures depends strongly on the stochastic nature (location, extent and magnitude) of the triggering rainfall event and less on local terrain conditions. The consideration of all landslides of such a cluster could bias the analysis by giving an excessive weight to the local terrain conditions (Depicker et al., 2020). Thus, for the shallow landslide susceptibility analysis (see Section 2.3.2), we retained a maximum of 30 landslides per cluster, randomly sampled in order to strengthen the statistical analysis and avoid overfitting. The choice of this selection is also guided by the concern to have at least the minimum of data required for training and validating the susceptibility models (Depicker et al., 2020). For the inverse Γ analysis, those landslides selected per cluster and other isolate landslides are called a distribution *minus event.*

2.4.2 Multi-decadal forest dynamics

In the study area, the agricultural land use is complex (multiple cropping, multi-layer farming) and highly dynamic due to crop rotations and associations, shifting cultivation, and the bimodal annual rainfall pattern (Heri-Kazi and Bielders, 2021b). Detailed regional land use mapping serving as an input variable in our susceptibility for shallow landslides and their distribution analysis (see Section 2.2.3) is therefore not feasible (e.g. Jacobs et al., 2018), which is an approach that differs from what can commonly be done in non-tropical environments (e.g. Chen et al., 2019; Shu et al., 2019). However, the dynamics of the forest can be better constrained. Here, to complement the year-to-year analysis conducted by Depicker et al. (2021b; see Section 2.2.1) that focused on the impact of deforestation on shallow landslides over the last 20 years, we reconstructed the forest dynamics over the last ~60 years (Fig. 2.2). We used the 1 m resolution orthomosaic generated from the RMCA's aerial photographs of the years 1955-1958 (Depicker et al.,2021a) with these photographs being the only existing pre-satellite-era source of information. The forest areas were delineated visually. The 2016 forest cover was extracted from the continental ESA Climate Change Initiative (CCI) land cover model which is available at a 20 m resolution (ESA, 2016). This satellite-based product has an accuracy of roughly 86 % in the region and has demonstrated its relevance in another study on landslides (Depicker et al., 2021a). Note also that between 2016 and 2019, i.e. the date that corresponds to the most recent images in Google Earth used for the inventory, very few forest cover changes were observed.

Knowing that the natural vegetation of the study area is forest (Section 2.2), in 1955-58, 42 % of the territory was already deforested (Fig. 2.2a). From 1955-58 to 2016, the loss of forest continued, with the forest cover decreasing from 58 % to 24 % of the study area. The area affected by the forest loss over the last 60 years is larger than the remaining permanent forest (Fig. 2.2b). The comparison of forest areas between 1955-58 and 2016 allows for considering four classes for the forest dynamics.

- Permanent forest corresponds to forest areas that are present at both dates.

- The forest loss class corresponds to forests present in 1955-58 that have disappeared in 2016. Since it is impossible to identify for each portion of the landscape the exact cause of forest loss, this class contains a mix of various forest management practices and other causes of forest cut/removal.
- The forest gain class represents the new forest that has appeared since 1955-58. Similarly, the causes associated with the occurrence of new forest are not exactly known, with afforestation and natural forest regeneration certainly being processes at play.
- Permanent anthropogenic environment (e.g. cropland, grassland, built-up land) means that the landscape was not forested in both dates, and it is assumed that it remained so during that period.

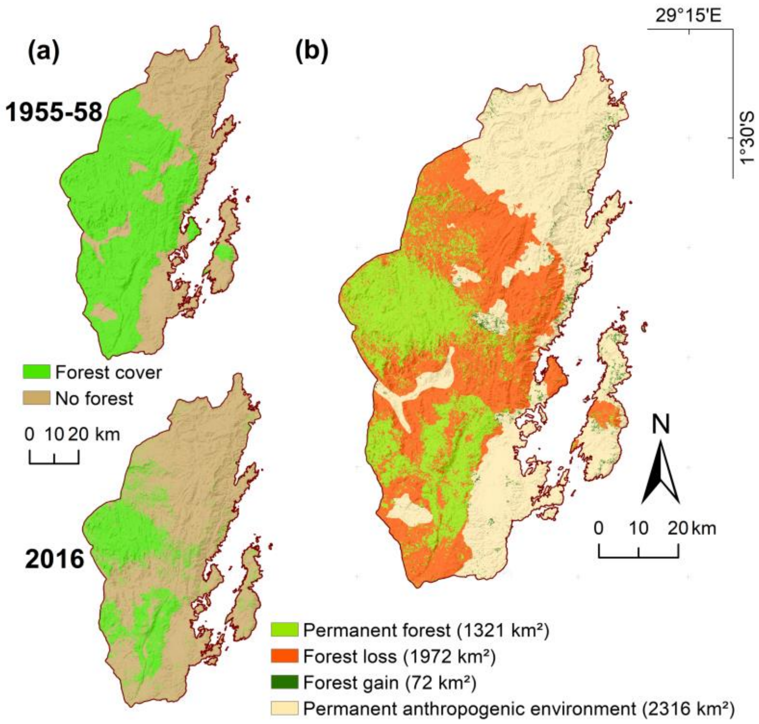


Figure 2. 2: *Forest cover dynamics over the last 60 years. (a) Forest cover in 1955-58 and 2016. (b) Areas of forest cover change between 1955-58 and 2016. Details for the images used in this figure are in Table 2.1.*

2.4.3 Landslide susceptibility and distribution analysis

Landslide susceptibility approaches are commonly used to determine the factors that control the occurrence of landslides. There are numerous approaches which are more or less complex in terms of modelling implementation, data needs and result interpretability (Reichenbach et al., 2018). Since our study aims neither to develop a new methodology nor to show the ability to use complex methods; we relied on a logistic regression approach (Hosmer and Lemeshow, 2000) to determine the predictor variables related to the occurrence of the different types of landslides. Logistic regression is a straightforward method demanding relatively few data that has been widely used (Reichenbach et al., 2018) and that allows for a rather easy interpretation of the results (e.g. Jacobs et al., 2018; Depicker et al., 2020).

Frequency ratio (Lee and Pradhan, 2007) models were used as a simpler but complementary approach to better understand the role of each variable in the contribution of the landslide occurrence in terms of process characterisation. For example, when slope angle is highlighted by a logistic regression model as a significant variable, we still remain unaware of the types of slopes that actually influence the occurrence of landslides.

The analysis was carried out according to the five categories of landslides defined in Section 2.3.1. The analysis was done at the scale of one point (pixel) per landslide to avoid spatial autocorrelation (e.g. Jacobs et al., 2018; Kubwimana et al., 2021). The point is manually positioned in the central region of the visually delineated landslide's source area to represent as close to reality as possible the conditions that caused its occurrence. In doing so we also avoid the selection of the highest point of the landslide that rarely corresponds to its initiation point (Dille et al., 2019). As stressed by Tanyaş et al., (2018), landslides growth with time. Therefore, considering one pixel per landslide instead of its whole source area allows for avoiding a temporally induced bias. The digital elevation model used for the analysis (see Table 2.1) is posterior to the occurrence of the old deep-seated landslides. Therefore, for deep-seated landslides, a point outside the source area where topography does not appear to have been disturbed by the instability is visually determined for the calculation of the slope associated with the landslide origin. Calculating the slope values at the level of the landslide source for this type of landslide would give values that are the consequences of landslides rather than the causes of their origin.

2.4.4 Predictor variables and landslide causes

The purpose of this research is to examine the predictor variables (**See Appendix Figure A.1** for the predictor variables not displayed in the main text) that contribute to the susceptibility of the different landslide categories. As such we mainly investigate the causes of the landslides. Nevertheless, the predictors highlighted by the susceptibility analysis may also help to discuss triggering conditions since the tectonic, landscape and climate of a region are commonly interlinked (Whipple, 2009; Whittaker, 2012).

We used eight predictors that can be considered natural factors that cause landslide occurrence (Table 2.1): elevation, slope angle, planar curvature, profile curvature, topographic wetness index (TWI), slope aspect, lithology and distance to faults. Although these predictors are commonly used (Reichenbach et al., 2018), it is worth specifying that, here, elevation is used as proxy for local climatic conditions, namely orographic rainfall and the probability of convective rainfall/thunderstorms, as the resolution of regional-climate-derived products is too low (at least 2.8 km) to accurately capture at the scale of our study area the effect of elevation on rainfall (Monsieurs et al., 2018a; Van de Walle et al., 2020). Distance to faults is used to determine the possible contribution of seismic activity in the occurrence of deep-seated landslides not only as a triggering factor (e.g. Keefer, 1984) but also as a measure of rock weathering factor (e.g. Vanmaercke et al., 2017). Using the fault pattern is the most appropriate option to tackle the seismic zonation context since the most detailed seismic hazard assessment for this part of the continent is at a spatial resolution of 2.2 km, i.e. at a resolution that is too coarse for our study (Delvaux et al., 2017).

Table 2. 1: *Landside predictor variables used for the susceptibility and frequency ratio analyses and the ancillary data from which they are derived.*

Variable	Type	Source
- Elevation (m)	Continuous	NASA Shuttle Radar Topography Mission (SRTM) Version 3.0 global 1 arc second data (temporal extent 2000-02-11 to 2000-02-21). https://lpdaac.usgs.gov/products/srtmgl1v003/ (accessed on 21 July 2022)
- Slope angle (°)	Continuous	
- Profile curvature (m^{-1})	Continuous	
- Plan curvature (m^{-1})	Continuous	
- Topographic wetness index	Continuous	
- Slope aspect (°)	Categorical	
• North	Dummy	
• Northeast	Dummy	
• East	Dummy	
• Southeast	Dummy	
• South	Dummy	
• Southwest	Dummy	
• West	Reference*	
• Northwest	Dummy	
- Lithology	Categorical	Geological map of the Kivu at 1/500,000 scale (Laghmouch et al., 2018)
• Old basalts	Dummy	
• Black shales and tillite	Dummy	
• Granites (mica and leucogranites)	Dummy	
• Granitic rocks (rhyolite)	Reference*	
• Pelites and quartzopelites	Dummy	
• Gneiss and mica schists	Dummy	
- Distance to faults (m)	Continuous	
Distance to roads (m)	Continuous	https://www.openstreetmap.org/history#map=9/-2.0475/28.5535 (accessed on 21 July 2022)
- Forest dynamics between 1955-58 and 2016	Categorical	Forest cover in 2016: (ESA, 2016: http://2016africalandcover20m.esrin.esa.int/viewer.php) (accessed on 13 March 2022) Forest cover in 1955-58: historical
• Permanent forest	Reference*	
• Forest loss	Dummy	
• Forest gain	Dummy	

• Permanent anthropogenic environment	Dummy	aerial photographs and derived orthomosaics from the RMCA (see Section 2.2.1)

* Each dummy variable is compared with the reference group.

Besides the natural factors, we identified two anthropogenic predictors (Table 2.1): forest dynamics and distance to roads. For the forest dynamics, we considered the four classes identified in Fig. 2.2. The main roads were retrieved from OpenStreetMap. Good knowledge of the study area and the analysis of the very high-resolution Google Earth images allowed us to verify the high accuracy of the road network proposed by OpenStreetMap. Using the historical photographs, we observe that the main roads date back to the colonial times and that no major changes in the network have occurred over the last 60 years. The few recent landslides that are observed in the field along these roads confirm the assumption that the direct impact of the main roads on the occurrence of recent landslides is currently limited. These landslides are clearly linked to the road cut topography, i.e. topographic conditions that cannot be constrained at the resolution of the SRTM elevation data (1″ or roughly 30 m). They are often of very limited size, i.e. at a size that is too small to be features that can be identified in Google Earth in a consistent manner. For our study, the distance to roads is taken as a proxy for human settlement, trail density, and intensity and diversity of agricultural practices. Since motorised transportation means are very limited in the region, the population growth, the expansion of villages and the agricultural activities are highly associated with the main road networks.

Prior to analysis, the predictor variables that were not topographically derived were resampled at the resolution of the SRTM DEM data; a resolution that is commonly used in many susceptibility analyses (Reichenbach et al., 2018). Furthermore, in a region of Uganda located in a relative proximity, Jacobs et al. (2018) evidenced that the 1 arc second SRTM DEM clearly outperforms higher-resolution products derived, in that specific case, from

TanDEM-X. The association between the dependent variable and each predictor variable was tested using the Pearson χ^2 test at a 95 % level of confidence (e.g. Van Den Eeckhaut et al., 2006). The predictors were tested for multicollinearity, variables with variance inflation factor (VIF) of > 2 being excluded from the analysis (e.g. Van Den Eeckhaut et al., 2006). The flat areas (slope angle < 1°) that are spread across the region were not excluded from the analysis since their total extent is limited and their impact on the inflation of susceptibility model performance would be minor (Brenning, 2012).

For the analysis of deep-seated landslides, the predictor variables associated with anthropogenic activities were excluded. For the shallow landslides, the "variable of distance to faults" was also excluded. As explained earlier, the shallow landslide inventory represents a narrow time window of observation. As such, the spatial distribution of the shallow landslides could be biased by the stochastic pattern of the recent heavy rainfall events and anthropogenic disturbances rather than reflecting the longer-term impact of weathering conditions associated with seismicity (Depicker et al., 2021a).

2.4.5 *Logistic regression*

Logistic regression is used to describe the relationship between a binary dependent variable (the presence or absence of landslides) and one or more independent predictor variables (Hosmer and Lemeshow, 2000). Hence, the logistic regression requires not only landslide data but also non-landslide data. We sampled this non-landslide data by generating a number of random points that is equal to the number of landslides in the inventory in order to avoid prevalence (Hosmer and Lemeshow, 2000). Non-landslide points were randomly generated outside a 40 m buffer zone around landslide areas. The basic equation for logistic regression is

$$\log\left(\frac{P}{1-P}\right) = \alpha + \sum_{i=1}^{n} \beta_i X_i \qquad (1)$$

where P is the likelihood of landslide occurrence and takes values between 0 and 1, α is the intercept of the model, X_i represents i-th of n predictors, and β_i the accompanying coefficient that has to be fitted to the data.

Calculations were performed in an RStudio environment (version 1.4.1717) with LAND-SE software (LANDslide Susceptibilty Evaluation; Rossi and Reichenbach, 2016). In order to be considered in the final logistic regression equation, continuous variable coefficients needed to be significant at the 95 % level of confidence (e.g. Jacobs et al., 2018). For categorical variables, as soon as one dummy variable was significant, all other dummy variables were included in the model (e.g. Depicker et al., 2020). The quality of the models was judged by (i) the prediction rate (e.g. Depicker et al., 2020); (ii) a visual plausibility inspection of the susceptibility maps after reclassifying each map into four classes of increasing susceptibility that cover 40 %, 30 %, 20 % and 10 % of the study area, and (iii) considering the area under the curve (AUC) of the receiver-operating-characteristics (ROC) curve. The AUC values vary between 0 and 1 and can be interpreted as the model's capacity of differentiating between landslide and non-landslide locations. An AUC of 0.5 shows that the model performance is equivalent to random classification, while an AUC of 1 indicates a perfect classification (Hosmer and Lemeshow, 2000). Training and validation datasets were taken in the proportions of 70 % and 30 %, respectively (Broeckx et al., 2018; Fang et al., 2020).

We assessed the importance of each individual predictor for the logistic regression in two ways. First, we calculated the AUC for landslide susceptibility models that only relied on the considered predictor to assess the extent to which this predictor can be used to differentiate between landslide and non-landslide locations. Although this is quite a straightforward approach that does not consider the possible interplay among predictor variables, this allows for a first quantitative insight into the importance of each variable to the susceptibility models (Depicker et al., 2020). A second way to determine the impact of the predictors was the analysis of the odds ratio (OR). The OR of a predictor expresses how a change of a predictor value translates into an increase/decrease in the odds of landsliding, whereby the odds of landsliding is calculated as $\frac{P}{1-P}$ (see Eq. (1)). The OR_i of predictor i is calculated as

$$OR_i = e^{\beta_i \delta_i}, \quad (2)$$

whereby β_i is the coefficient of predictor i and δ_i is the increase in predictor i. For continuous variables an arbitrary but realistic value for δ_i is chosen. For the dummy variables, δ_i equals 1. For the categorical variables, the OR for each dummy reflects an increase or decrease relative to the reference variable (Kleinbaum and Klein, 2010).

2.4.6 *Frequency ratio*

The frequency ratio model considers each landslide predictor variable individually and classifies its values into a set of bins to indicate for each bin of the predictor variable the probability of occurrence of a landslide (Lee and Pradhan, 2007; Lee et al., 2007; Kirschbaum et al., 2012). The frequency ratio is calculated as

$$\mathrm{Fr}_{cb} = \frac{\mathrm{a}_{cb}/\mathrm{a}_{\mathrm{T}}}{\mathrm{A}_{cb}/\mathrm{A}_{T}}, \quad (3)$$

where $\mathrm{Fr}_{\mathrm{cb}}$ is the frequency ratio value for bin $b = (1,2, \ldots, n)$ of predictor variable $c = (1, 2, \ldots, \mathrm{m})$, a_{cb} is the cumulative landslide area within bin b of predictor c, a_T is the cumulative landslide area in the entire study area, A_{cb} is the area attributed to bin b of predictor c and A_T is the total extent of the study area.

2.5 Results

Landslide inventory

Overall, we mapped 2730 landslides (Fig. 2.3a; Table 2.2). The landslides are diverse in terms of size, age and type (Fig. 2.4). The inventoried landslides cover ~3 % of the study area. The largest landslide is an old and deep-seated complex movement (426 ha), while the smallest detected landslide is a shallow debris avalanche (16 m^2). The landslides are grouped into five categories (Fig. 2.3a; Table 2.2)

- Old deep-seated landslides represent 45,5 % of the inventoried landslides and cover 93 % of the total landslide-affected area. Most of these landslides are of the rock slide type. Rock avalanches, although much less frequent, are also present. Rockfalls can be associated with the presence of the main scarps of these old landslides. However, they have not been considered in the inventory and the subsequent analysis.
- Shallow landslides represent 40.4 % of inventoried landslides but represent only 2.7 % of the total affected area. Most of these landslides are of the debris avalanche type. These landslides are all recent and clearly associated with rainfall. The landslides clustered events all fall into this category.
- Recent deep-seated landslides represent a small percentage of landslides (5.8 %) but cover an area (2.9 %) similar to that of shallow landslides. Most of the landslides are of the slide type. Their trigger, when identified, is associated with rainfall.
- Mining landslides (that also include quarrying landslides) represent 5.6 % of the inventoried landslides and cover 1.2 % of the total landslide-affected area.
- Regarding road landslides, the inventory shows that 115 landslides are located within 50 meters of roads: 60 of these landslides are shallow, 13 are recent and deep-seated, 35 are old and deep-seated, and 7 are mining landslides. Only the shallow

and recent deep-seated landslides were classified as road landslides i.e. a total of 73 landslides. The old deep-seated landslides located close to roads were retained in the old deep-seated landslide category because their timing is likely to precede road construction. The mining landslides were also retained in their respective category.

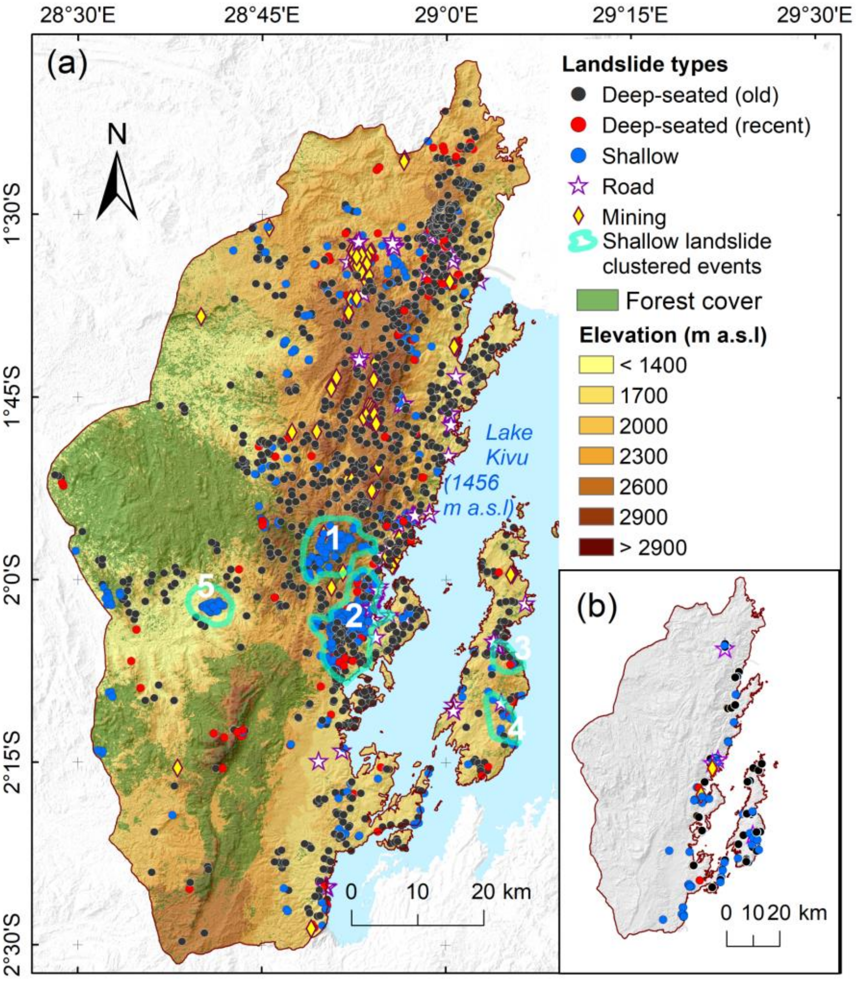


Figure 2. 3: *(a) Landslide inventory obtained from the image analysis and extent of the forest cover in 2016 (after ESA, 2016). Numbers represent clusters of shallow landslides that are associated with heavy rainfall events dated in ascending order from oldest to most recent. (b) Additional landslides identified only in the field.*

We identified several shallow landslides clustered events. One of the events is related to the Kalehe rainstorm of 25 October 2014 (Fig. 2.3a: event 2; Fig. 2.4a) reported by Maki Mateso and Dewitte (2014). This rainfall triggered 634 shallow landslides, 346 of them being connected to talwegs and providing materials to 17 debris flows. A total of 10 debris flows were particularly destructive and deadly when they reached villages on the shores of Lake Kivu (Maki Mateso and Dewitte, 2014). In this area, 14 shallow landslides present on Google Earth images before this event were reactivated. Field observations and interviews with local populations confirmed that the shallow landslides that are not associated with these clustered events are also rainfall-triggered.

Table 2. 2: *Typology, size properties, and identification methods of the inventoried landslides (LS). The percentages of landslides linked to the TanDEM-X hillshade images (% of LS in TanDEM-X) represent landslides that could not be very well identified in © Google Earth alone.*

Landslide type	Number of LS	% of LS	% of LS area	Max area (ha)	Min area (m^2)	Average area (ha)	Standard deviation (ha)	% of LS in ©Google Earth	% of LS in TanDEM-X
Deep-seated (old)	1243	45.5	93.0	426.4	604	12.6	26.8	94.9	5.1
Deep-seated (recent)	159	5.8	2.9	28.9	210	3.1	5.4	97.5	2.5
Shallow	1103	40.4	2.7	53.8	16	0.4	2.4	100	0
Mining	152	5.6	1.2	13.4	99	1.4	1.9	100	0
Road	73	2.7	0.1	2.0	149	0.3	0.3	100	0
All landslides	2730	100	100			6.2		97.5	2.5

Table 2. 3: *Field-based validation of the landslides (LSs) inventoried from the image analysis. True positive (TP): landslides that were mapped in the images and validated in the field. False positive (FP): landslides that were mapped in the images but not validated in the field. False negative (FN): landslides that were identified solely in the field. Precision: TP / (TP+TN)*

Landslide type	Number of LSs mapped in the images and checked in the field	TP	FP	FN	Precision (%)	Total number of LSs viewed in the field
Deep-seated (old)	248	239	9	60	96	308
Deep-seated (recent)	47	44	3	4	94	51
Shallow	426	420	6	55	99	481
Mining	15	9	6	2	60	17
Road	50	45	5	5	90	55
Total	786	757	29	126	96	912

Landslide mapping was largely done using Google Earth; with the TanDEM-X hillshade images being useful to confirm the identification of about one-fifth of the old deep-seated landslides (Table 2.2). Fieldwork carried out to validate 786 landslides (25% of the inventory) showed that they were identified with a precision (TP/(TP + FP) of 96 % (Table 2.3). Old deep-seated landslides and shallow landslides were mapped with the highest precision. Mining landslides were mapped with a lower precision due to the difficulty of differentiating between landslide processes and anthropogenic soil disturbance in Google Earth imagery. The field validation allowed for also mapping an extra 126 landslides (Fig. 2.3b) that could only be identified in the field (Table 2.3).

For the old deep-seated landslides, this represents an extra 24% of observations (Table 2.3: see column FN). Nevertheless, landslides identified only in the field were not considered in the analysis to avoid biases due to overrepresentation.

Each debris flow is connected to up to hundreds of shallow landslides that act as source areas. A clear distinction was made between these sources and the debris flow path and deposition areas (Fig. 2.4a). Out of a total of the 184 debris flows identified from the images, 90 with a length-to-width ratio of > 50 were excluded from the analysis since they show greater similarities to debris-rich floods than to the other landslides present in the region (Malamud et al., 2004). Nevertheless, the shallow landslides acting as source areas were kept in the analysis. Also, 22 very large, old, deep-seated landslides were excluded from the analysis because they have complex main scarps where it is difficult to determine the pixels that best represent the natural conditions of occurrence. Overall, from the 2730 landslides identified from the images, 2618 landslides were used for the subsequent analysis.

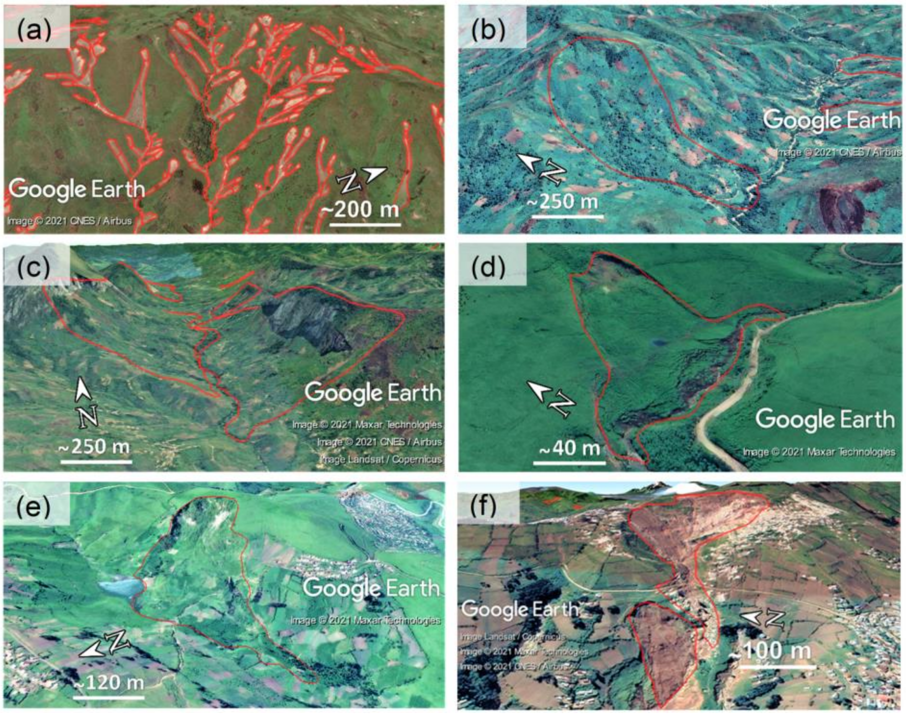


Figure 2. 4: *Examples of landslide types (according to Varnes' new classification – Hungr et al., 2014). (a) Cluster of recent debris avalanches and debris flows triggered during an intense rainfall event (25/10/2014) in the vicinity of Kalehe (2.041°S, 28.874°E); the image illustrates a part of the landslides clustered event 2 shown on Fig. 2.3a). The source areas of these shallow landslides are identified. (b) Old earthflow (2.053°S, 28.660°E). (c) Old rock slides/rock avalanches/ with path-dependent rockfalls (2.007°S, 28.708°E). (d) Recent deep-seated rotational slide that occurred in 2002 (1.530°S, 28.708°E). (e) Recent deep planar slide that occurred in 1994 and created a dammed lake (1.521°S, 28.977°E). (f) Recent slides, flows and avalanches associated with mining activities that occurred from 2013 onwards (1.563°S, 28.885°E).*

Except for the recent deep-seated and mining landslides, the inverse gamma (Γ) distribution fits the distributions for the other categories of the inventory well (Fig. 2.5a,b) which supports their use for further susceptibility analysis. The Wilcoxon rank comparison test confirms significant statistical differences (p-value < 0.05) among the area distributions (Fig. 2.5c).

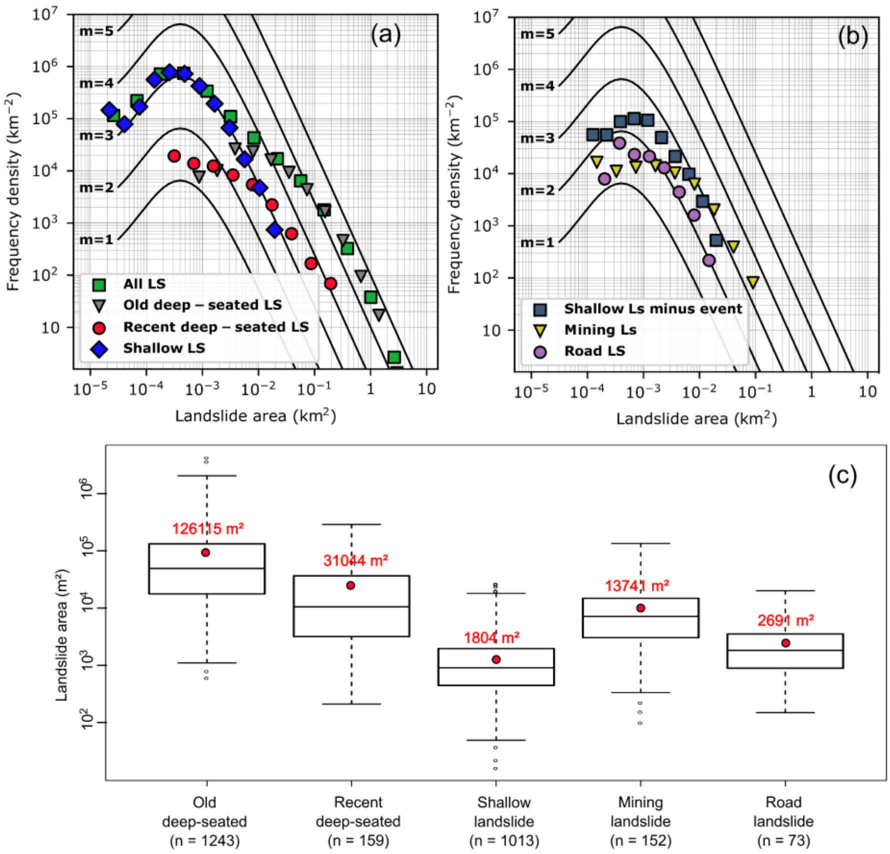


Figure 2. 5: *Landslide (LS) area characteristics. (a, c) Landslide frequency-area distributions for each landslide category. (b) Boxplots showing the distribution of landslide area for each landslide category. Boxplots show the lower and upper quartiles and median. The whiskers of each box represent 1.5 times the interquartile range. The average area of the landslides (red dots) is provided for each boxplot and the outliers beyond whiskers are shown as dots. The number of landslides in each category is shown in brackets.*

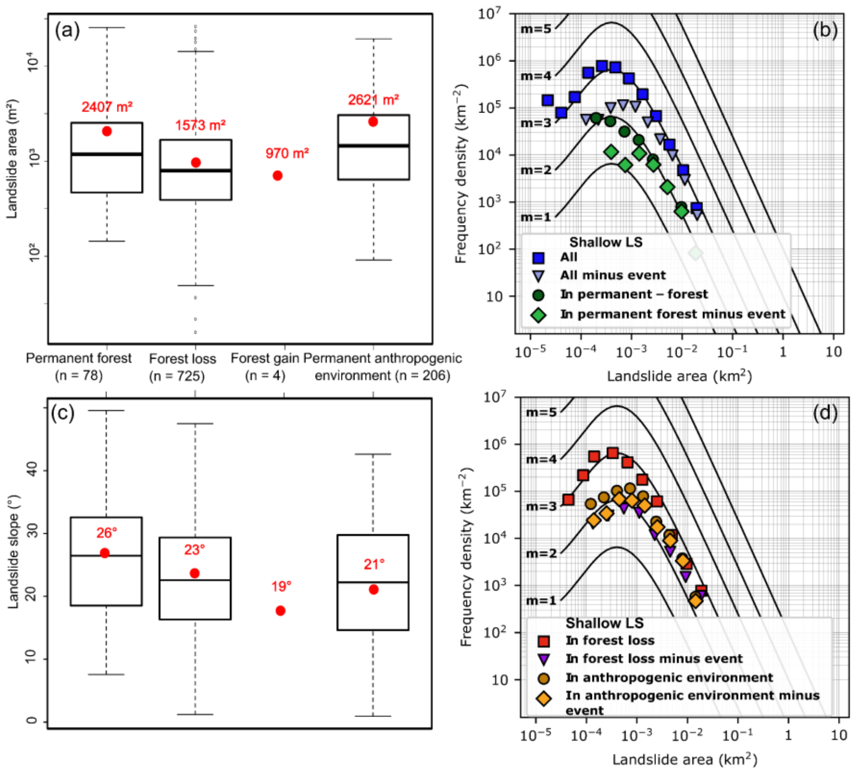


Figure 2. 6: *Shallow landslide characteristics and forest cover dynamics. (a, c) Boxplots showing the distribution of landslide area and landslide slope, respectively, for each land cover class. A detailed description of boxplots is provided in Figure 2.5. (b, d) Shallow landslide frequency-area distributions for each land cover class.*

A majority (72 %) of the shallow landslides is found in areas of forest loss (Fig. 2.6). The landslides in the permanent anthropogenic environment have the largest mean area, followed by the landslides in permanent forest and the landslides in areas of forest loss. In forest gain zones, landslides are on average the smallest. The Wilcoxon rank comparison test confirms significant statistical differences (p-value < 0.05) among the landslide area distributions. The same differences are also confirmed for the landslide slope distribution (Fig. 2.6b). In permanent-forest areas, shallow landslides occur on steeper slopes compared to shallow landslides in anthropogenic environments (Fig. 6b). The analysis of the completeness of the inventory (Fig. 2.6b,d) shows that an acceptable distribution emerges for each category of shallow landslides except for the landslide inventory in the permanent forest minus event (Fig. 2.6b).

2.5.1 Landslide susceptibility and distribution analysis

The Pearson χ^2 tests confirm the association between the dependent variable and each predictor variable at a 95 % level of confidence. There was no multicollinearity between the predictors (VIF < 2) retained for this study.

For examples, Thiery et al. (2007) and Depicker et al. (2020) assessed the impacts of the size of the landslide training dataset to calibrate a landslide susceptibility model. They showed that the quality of a susceptibility assessment is questionable if the number of landslides is too small. In view of the low number of recent deep-seated, mining, and road landslides in the present study (Table 2.3), we did not calibrate susceptibility models from these three types of landslides. Instead, we tested these inventories against the two susceptibility models computed from the shallow and/or old deep-seated landslide datasets, from which we could derive prediction rates (Fig. 2.7).

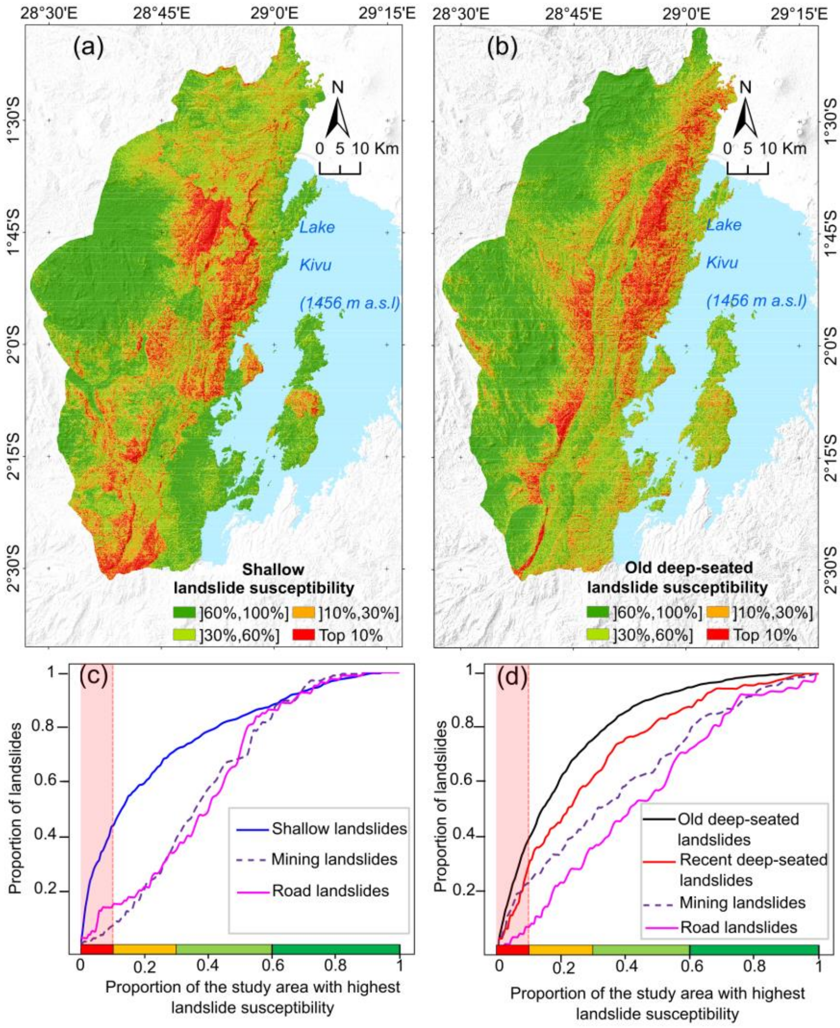


Figure 2. 7: *Landslide susceptibility models and prediction rates. (a) Shallow landslides (AUC: 0.78). (b) Old deep-seated landslides (AUC: 0.82). (c) Prediction rate curves for shallow, mining, and road landslides; (d) prediction rate curves for old deep-seated, recent deep-seated, mining and road landslides. The red-shaded area in panels* ***(c)*** *and* ***(d)*** *represents the 10 % of the region with the highest landslide susceptibility values.*

The univariate AUC values are all above 0.5 (Table, 2.4). All predictors considered for both categories of landslides were thus considered in the multivariate logistic regression models. The two susceptibility models of shallow and old deep-seated landslides show similar AUC and prediction rates (Fig. 2.7). At first sight, both models have spatial similarities of high susceptibility on the eastern part of the region; while the entire western part is less susceptible (Fig. 2.7a,b). However, when we go into detail, the spatial patterns of the susceptibility values of the two models are quite different as it reflects the differences in the importance of the predictors included in the assessment (Table 2.4, Table 2.5).

Table 2. 4: *Relative importance of the predictors of the logistic regression models for shallow and old deep-seated landslides based on AUC_i (ranked in descending order).*

Shallow landslides		Old deep-seated landslides	
Predictor	AUC_i	Predictor	AUC_i
Forest loss	63	Profile curvature.	65.7
Elevation	61.5	Elevation	65.3
Slope angle	60.1	Distance to faults	64.2
Distance to roads	59.7	Slope angle	64
Pelites and quartzopelites	58.9	TWI	63.8
Permanent anthropogenic environment	55.9	Plan curvature.	59.5
TWI	55.3	Pelites and quartzopelites	54.5
Plan curvature.	53.1	South	52.4
East	52.2	Northeast	52
Southeast	52.2	North	51.6
Black shales and tillite	51.8	East	51.1
Old basalts	51.8	Southeast	50.7
North	51.8	Granites (mica and leucogranites)	50.7
Granites (mica and leucogranites)	50.8	Old basalts	50.5
Southwest	50.7	Gneiss and mica schists	50.5
Gneiss and mica schists	50.6	Southwest	50.3
South	50.6	Black shales and tillite	50.3
Profile curvature	50.4	Northwest	50.2
Northeast	50.4		
Northwest	50.1		
Forest gain	*		

* Only four landslides are present in this category.

Table 2. 5: *Results of the logistic regression (LR) models for shallow landslides and old deep-seated landslides.*

		Shallow landslides			Old deep-seated landslides			Step
AUC		0.78			0.82			δ_i
Predictor variable		LR coef.		Odds ratio	LR coef.		Odds ratio	
(Intercept)		-3.560	***		-1.661	***		
Elevation		0.001	***	1.857	0.002	***	2.535	500
Slope aspect	Northwest	0.842	*	2.321	-0.366		0.694	1
	West	Ref.	-		Ref.	-		
	Southwest	0.674	*	1.962	-0.232		0.793	1
	South	0.630	*	1.878	0.032		1.033	1
	Southeast	0.599		1.820	-0.345		0.708	1
	East	0.513		1.670	-0.578	**	0.561	1
	Northeast	0.622		1.863	-0.897	***	0.408	1
	North	0.481		1.618	-0.831	***	0.436	1
Plan curvature		-0.272	*	0.580	0.166	***	1.394	2
Profile curvature		-0.190		0.999	-0.463	***	0.998	0.005
Slope angle		0.050	***	1.649	0.033	***	1.391	10
Topographic wetness index		0.093		1.000	-0.281	***	1.000	0.001
Lithology	Old basalts	-0.753	-	0.471	0.201		1.223	1
	Black shales and tillite	-1.207	***	0.299	-1.358	***	0.257	1
	Granite leucogranites	-17.026	-	0.000	-2.126	***	0.119	1
	Granitic rocks (rhyolite)	Ref.			Ref.			
	Pelites and quartzopelites	-1.274	***	0.280	0.155		1.168	1
	Gneiss and mica schists	0.506		1.659	-0.468		0.626	1
Distance to roads		0.000	***	0.931	no	-		500
Distance to faults		No	-		0.000	***	0.914	500
Forest cover dynamics	Permanent forest	Ref.	-		No	-		
	Forest loss	0.922	***	2.514				1
	Gain forest	No	-		No	-		

Permanent anthropogenic environment	-0.159	0.853	No	-	1

No = variable not included in the logistic regression model
Ref. = reference category of the dummy variable
Coefficient included in the logistic regression model = *p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

Forest loss has a large influence on the occurrence of shallow landslides as deforestation increases the odds of landsliding by a factor of 2.5 (Table 2.4, Table 2.5). However, anthropogenic environments appear to be less landslide-prone than permanent forest. Elevation and slope angle are similarly important for the prediction of both types of landslides (Table 2.4) but have a slightly larger impact on the odds of deep-seated landsliding that on the odds of shallow landsliding (Table 2.5). Slope aspect has a greater impact on the occurrence of shallow landslides than on that of old deep-seated landslides. It appears that the plan curvature reduces the occurrence of shallow landslides, while it favours the occurrence of old deep-seated landslides. The effect of lithology is also different for shallow and deep-seated landslides. For shallow landslides, the gneiss and mica schists are most landslide-prone and the lowest susceptibility is associated with black shales, tillite and old basalts. For deep-seated landslides, black shales, tillite and old basalts favour landslides, while gneiss and mica schists do not. Distance to roads and distance to faults have a significant but rather limited impact on shallow and old deep-seated landslides, respectively.

Mining and road landslides are poorly predicted using the shallow landslide model (Fig. 2.7c). The prediction of road and mining landslides using the deep-seated model is also poor, although less problematic for the mining landslides (Fig. 2.7d). Recent deep-seated landslides are reasonably well predicted using the old deep-seated landslide model, which validates to some extent the multi-temporal predicting performance of the assessment.

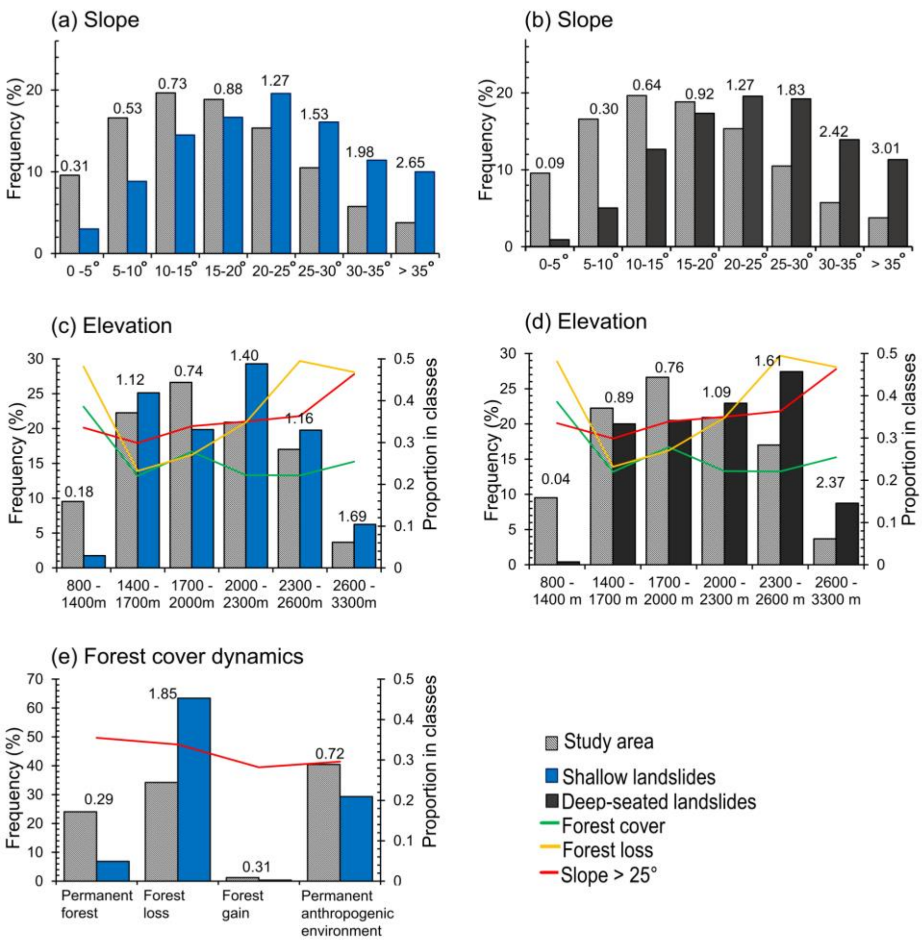


Figure 2. 8: *Frequency distribution for shallow and deep-seated landslides in a function of key predictor variables. Panel (c), (d) and (e) allow for a multivariate comparison of the predictors. The corresponding frequency ratio is shown for each class above the vertical bars. The green, orange and red curves indicate the proportion of forest cover, forest loss and slope > 25°, respectively, in the different classes of the predictor variables.*

Slope angle is an important driver for shallow and old deep-seated landslides (Fig. 2.8a,b). Both types of landslides are favoured by slopes angles of > 20-25°. We observe a trend in the landscape of increasing slopes and forest loss and decreasing forest cover with increasing elevation (Fig. 2.8c). The decrease in forest cover at high elevations is also associated with a natural change of the vegetation: bamboo vegetation is found at 2300-2600 m asl and subalpine vegetation such as ferns occurs at 2400-3300 m asl (Mokoso et al., 2013; Cirimwami et al., 2019). At higher elevations (> 2000 m), shallow landslides occur more frequently, and this can probably be explained by a cumulative effect of forest loss, steeper slopes and increased orographic rainfall associated with these elevations (Fig. 2.8c). The positive frequency ratio in the 1400-1700 m elevation class is related to the area of permanent anthropogenic environment. This zone is characterized by low forest cover and relatively low slopes (Fig. 2.8c). Deep-seated landslides are also favoured by steeper slopes and higher elevations. Regarding the dynamics of forest cover (Fig. 2.8e), the occurrence of shallow landslides is favoured in the deforested areas.

2.6 Discussion

2.6.1 Landslide types and completeness of the inventory

Despite its high precision and the fact that with more than 2700 mapped landslides we have identified more than 3 times as many features as in the inventory of Depicker et al. (2020), we are aware that the dataset is still incomplete. This is particularly the case for the shallow landslides because their inventory covers a maximum period of 13 years. Furthermore, their scars can quickly be altered by natural vegetation regrowth, land reclamation and erosion (Malamud et al., 2004; Van Den Eeckhaut et al., 2007; Kubwimana et al., 2021; Dewitte et al., 2022); although, here, since we have used several image covers from Google Earth, this issue is nuanced. In addition, small landslides frequently happen unnoticed at the resolution of the satellite images (Guzzetti et al., 2012). Finally, field validation showed that a significant proportion of old deep-seated landslides can be missed from image analysis (Table 2.3). This is because recognising old deep-seated landslides may not be easy, particularly in forest areas (Malamud et al., 2004). While building the inventory, we remained conservative and mapped only the features for which we had high confidence. As the protocol for landslide identification over the whole region was uniform and the number of identified landslides was relatively important, we trust that the inventory is reliable and representative enough for the analysis.

The frequency-area distributions of all landslides categories (Fig. 2.5a,b), with the exception of recent deep-seated and mining landslides, are similar to what has been observed in other parts of the world (e.g. Malamud et al., 2004; Guns & Vanacker, 2014; Jacobs et al., 2017; Rault et al., 2022). For the recent deep-seated landslides, an overrepresentation is noticed at the level of the smallest landslides and the rollover is absent. Since the spectral signature of these landslides is pronounced, we cannot invoke here a problem of subjectivity in the mapping. Additionally, we can give a high trust score in the completeness of the inventory as evidenced by field validation that showed that almost no landslides were missed (Table 2.3). Therefore, we posit that this divergence in size is related to a lower influence of successive slope failure in the increase in landslide area through time; in other words, recent landslides did not have the time to grow (Tanyaş et al., 2018). This process of successive failures has been well documented for the Ikoma landslide, south of Bukavu (Figure 2.1b; Dille et al., 2019). The distribution of the mining landslides is irregular and different from what is typically observed, with a rollover that is flattened and a sudden increase in the frequency of the smallest slope failures. Similarly, to the inventory of the recent deep-seated landslides, the completeness and the reliability of the mapped features cannot be questioned much. We suggest that this unusual area distribution is the result of the human-induced alteration of the environmental conditions (see Section 2.4.4). To our knowledge, there are apparently no similar studies that have been carried out on artificial mining slopes. Further investigations on other cases would be needed to verify our hypothesis.

The presence of a rollover in the frequency-area distribution of the shallow landslides in the anthropogenic environment (Fig. 2.6b,d), compared to tropical mountains (Guns and Vanacker, 2014) is in opposition to what we could have expected considering the study by Van Den Eeckhaut et al. (2007). This study was also conducted in a densely populated rural environment and also relied on an inventory that is not associated with one single landslide-triggering event. They did not find a positive power-law relation for the smaller landslides which are separated from the larger landslides by a rollover. This difference probably lies in the fact that our study area is much more landslide-prone. The research by Van Den Eeckhaut et al. (2007) was indeed carried out in a hilly region of Belgium where the temperate climate is much less favourable to the yearly occurrence of shallow landslides. Furthermore, the fact that our inventory covers a smaller time period than that of Van Den Eeckhaut et al. (2007); that our region is not altered by mechanised farming; and that human activities such as works associated with building and road construction and drainage systems are much less present, i.e. factors that are highlighted as causes of landslides in Belgium, are issues that can also be invoked to explain this divergence in the frequency-area distribution of shallow landslides.

Under permanent forest, we do not observe a rollover point in the shallow landslide distribution, (Fig. 2.6b). We hypothesise that the smallest landslides may be hidden under the canopy and therefore less visible on satellite images. A second explanation is that the presence of trees and their roots increases slope stability and therefore the minimal critical area for landsliding (Milledge et al., 2014).

2.6.2 Drivers of deep-seated landslides

The old deep-seated landslide susceptibility model is the first model proposed for the region that focuses only on deep-seated processes. The model shows a good quantitative prediction performance, both in terms of AUC and prediction rate. The model shows that terrain morphology and seismic activity seem to play a dominant role in deep-seated landslide distribution in the study area. The frequency ratio analysis (Fig. 2.8b,d) further supports this as it highlights the association of landslides with steep slopes and higher elevations, i.e. in topographic contexts nearer to the ridge crests that are known to amplify seismic shaking (Meunier et al., 2008). The role of elevation as a driver of more humid conditions should, however, not be ignored as rainfall is also known to trigger deep-seated landslides (LaHusen et al., 2020). Also, the role of the long-term weathering of the landscape and the occurrence of non-triggered landslides should not be underestimated (Dille et al., 2019). Lithology is of lesser importance in our study area, which is in agreement with the findings of Depicker et al. (2021b) that show that at the regional scale, the various lithologies have similar rock strength properties. However, with better defined lithological information, local specificities would certainly appear (Kubwimana et al., 2021). As we also show that the topography and the presence of faults play a role, it is another factor that can explain that the influence of lithology is somehow limited.

The lower prediction rate of the recent deep-seated landslides using the old deep-seated landslide model could be related to the fact that the observations are made on a period that is too short to apprehend the full panel of environmental conditions that led to old deep-seated landslides. For example, no earthquake-induced recent deep-seated landslides were observed (Dewitte et al., 2021), whereas seismicity is an important component of the old deep-seated landslide model. In addition, the climatic and seismic conditions have evolved over the past tens of thousands of years (Felton et al., 2007; Wassmer et al., 2013; Ross et al., 2014; Smets et al., 2016). For example, the region experienced an abrupt shift from drier conditions to more humid conditions around 13,000 BP (Felton et al., 2007; Wassmer et al., 2013). In addition, at about 10,000 BP, Lake Kivu water highstands were

~100 m above the current level, which could have triggered few large landslides (Ross et al., 2014; Dewitte et al., 2021). This change in the lake level was due to not only a shift in the climatic conditions but also the formation of the Virunga Volcano Province that created a dam on the upstream part of the rift basin that used to drain northwards (Figure 2.1b; Haberyan and Hecky, 1987). During that period of volcano formation, the regional geodynamics and the seismicity pattern were different (Smets et al., 2016). Hence a large part of the old deep-seated landslides may have been triggered under different conditions.

Old and recent deep-seated landslides differ also in terms of size (Fig. 2.4). There have not been any major events during the past 60 years that caused large landslides comparable to the largest old deep-seated landslides (area of 10^6 m^2). We identify five possible factors to explain this difference. First, our window of observation is too narrow to apprehend the impact of forcing events of high-magnitude such as large earthquakes (Marc et al., 2019). Second, the past environmental conditions may have been more favourable to large slope failures. A third factor explaining the size difference between old and recent deep-seated processes is that larger landslides are less frequent but have a longer-lived morphology legacy; therefore smaller old deep-seated landslides may no longer be visible. The fourth factor is that old landslides have a size that is the legacy of a history of phases of slope deformation, and not one single slope failure (Tanyaş et al., 2018). Fifth, amalgamation must not be excluded (Marc and Hovius, 2015), especially for the oldest features. Overall, our current knowledge does not allow for giving more credit to one factor in particular. Common sense would to assume that the difference in landslide size is the reflection of a combination of factors.

2.6.3 Drivers of shallow landslides

Rainfall is the trigger of the shallow landslides that we have identified in this study, which is in agreement with the other studies in the region (Dewitte et al., 2021; Kubwimana et al., 2021). The spatial distribution of shallow landslides differs from the distribution of deep-seated landslides. This is mainly due to the anthropogenic factors such as deforestation that influence shallow processes (Table 2.4). The regional susceptibility model also indicates that deforestation is the most important factor in their occurrence (Table 2.5). Similarly, the analysis of frequency ratios shows that landslides disproportionately occur within areas that were deforested in the past 60 years, demonstrating the role of the forest in slope stabilisation (Grima et al., 2020).

Shallow landslides in forest loss areas (Fig. 2.6a,b) have, on average, a smaller size compared to landslides in forest. This observation is in line with the findings of Depicker et al. (2021b) and is attributed to the decrease in regolith cohesion by reduced root cohesion and evapotranspiration due to forest loss (Glade, 2003; Masi et al., 2021), which allows for a smaller minimum critical area for landsliding (Vanacker et al., 2003; Milledge et al., 2014). In short, human-induced land cover change is associated with an increase in the number of landslides and a shift of the frequency-area distribution towards smaller landslides (Guns and Vanacker, 2014).

In permanent anthropogenic environments (Fig. 2.6a,c), shallow landslides are less frequent and larger and occur on less steep slopes as compared to shallow landslides in forest. Firstly, the steepest slopes in the anthropogenic environments have been subject to increased landslide erosion the first few years after the original forest cover was removed (prior to 1955-1958) (Depicker et al., 2021a). As a result, we can assume that steep slopes in anthropogenic environments have less regolith available for landsliding compared to similar steep slopes in permanent-forest areas. This process of regolith depletion is further exacerbated in cropland. Wilken et al. (2021) have measured in the region that erosion in cropland sites can reach up to about 40 cm in 55 years. Similarly, Heri-Kazi and Bielders (2021a) measured mean erosion rates of the order of 11 mm/year on cropland. Regolith erosion has therefore the consequence of reducing the spatial extent of areas where landslides can occur. A second process that may explain the landslide pattern in the anthropogenic environments is that, in parallel to regolith erosion, one also has sedimentation and the formation of colluvium (Wilken et al., 2021), which results in local accumulation of material. The material forms a loose sedimentary deposit usually in places with lower slope angles. This could be extra material available for the formation of landslides with the colluvium supply and a minimum depth of material being recognised as playing a key role in the occurrence of shallow landslides (Parker et al., 2016). Hence, we have less areas available for landslides but a concentration of the susceptible places. A third explanation is probably related to soil management practices that influence erosion and water infiltration. In the region, usually on the less steep terrain, drainage ditches that favour water infiltration and hence an increase in porewater pressure are widely applied by farmers (Heri-Kazi and Bielders, 2021b).

2.6.4 Drivers of mining landslides and road landslides

The poor prediction rates of mining and road landslides when compared to the two shallow and deep-seated susceptibility models (Fig. 2.7) show that they respond to different environmental factors. Road construction and mining activities are commonly associated with the presence of slope cuts and an increase in slope angle. These altered local topographic conditions cannot be constrained in the covariates derived from the SRTM or similar available products. In addition, the disturbances induced by roads and mining activities are not limited to the sole change of slope angle conditions. For example, this also implies changes in water runoff and infiltration, debuttressing, presence of fills and eventual overloading, and excess stress from engine/digging, i.e. conditions that can influence the size and frequency characteristics of landslides (Brenning et al., 2015; Arca et al., 2018; Froude and Petley, 2018; McAdoo et al., 2018; Vuillez et al., 2018; Tanyaş et al., 2022).

Road landslides are mostly shallow. While it is obvious that roads create favourable conditions for the initiation of landslides, as observed not only in the region (e.g. Kubwimana et al., 2021), but also worldwide (Froude and Petley, 2018; Sidle et al., 2006; Brenning et al., 2015; Arca et al., 2018; McAdoo et al., 2018; Vuillez et al., 2018; Muñoz-Torrero Manchado et al., 2021; Tanyaş et al., 2022), an accurate spatio-temporal regional pattern of these human-induced slope failures cannot be assessed here. A substantial proportion of road landslides can only be observed in the field (Table 2.3). In addition, landslides along roads can easily disappear due to maintenance works. Furthermore, many of the main roads were already present in the 1950s, with their current impact therefore being altered.

Overall, mining conditions seem to lead to landslides whose smallest features are more frequent than what would occur under natural conditions as attested in the frequency-area distribution (see Section 2.4.2). The area of mining landslides is significantly larger than that of road landslides, and their regional distribution is slightly more in agreement with the characteristics of deep-seated landslides (Fig. 2.7d), which is logical as mining activities are related to the lithological characteristics of the landscape, i.e. a cause that typically has more influence on deeper processes (Migoń, 2013; Dille et al., 2019).

Considering the recent development of the mining activities in the region (Butsic et al., 2015; Tyukavina et al., 2018; Musumba Teso et al., 2019), we can assume with confidence that the associated landslides represent slope instabilities that have occurred over a period of about 20 years whereas the recent deep-seated landslides represent slope failures that have occurred over the last 60 years. The distribution of the mining landslides is also restricted spatially to some lithologies. With these specificities in mind and the fact that the number of inventoried mining and recent deep-seated landslides is relatively similar, respectively 152 and 159 (Table 2.2), this study confirms that mining activities increase the odds of landsliding. It has implication not only in terms of susceptibility assessment but also in assessing the population at risk, knowing that mined sites are populated. This is to be put in parallel with the findings of Depicker et al. (2021a) that show that the risk of shallow landslides has increased significantly in the region during the last decades in the places where mining activities are found due, notably, to an increase in population.

2.7 Conclusions

The use of several sources of data allowed for building a very detailed and comprehensive landslide inventory in time and space for the region, a source of information unprecedented in such environments. This inventory enabled the grouping of landslides into five categories: old (pre-1955) and recent (post-1955) deep-seated landslides, shallow landslides, mining landslides, and road landslides. Among deep-seated landslides, historical aerial photographs from the 1950s were an added value in the sense that they were used for differentiating between old and recent slope processes. We deduce the differences in the driving factors and area distribution for old and recent deep-seated landslides, suggesting that factors of landslide occurrence are either different or change over time depending on geodynamic and/or climatic conditions. The role of anthropogenic factors has been established in the occurrence of shallow landslides. Deforestation initially increases landsliding, but in the long term, when forest is permanently converted into agricultural land, landslide frequency appears to be lower compared to permanent-forest lands. The impact of forest, forest cover changes and soil management practices depends on topographic conditions and regolith availability. The factors of occurrence of mining landslides significantly increase landsliding in areas that, under natural conditions, would be less prone to slope failures. Our analysis shows that the importance of human activities must be considered when investigating landslide occurrence in regions under anthropogenic pressure. This is particularly needed when one sees that the changing spatio-temporal patterns of landslides associated with these activities tend to further exacerbate the risks that the population face.

On a more technical/methodological note, our study also demonstrates the importance of considering the timing and the depth of landslides as well as the differentiation between mining and road landslides. While several well-known landslide classification systems are used at the international level (Hungr et al., 2014; Sidle and Bogaard, 2016), these systems are not framed around the combination of the differentiation criteria that are used in this research. Our study does propose a unique effort at classifying landslide types in order to investigate them in the context of the Anthropocene. We believe that our mapping effort and classification protocol is the most adapted (based on field observation and understanding of the landscape) in this case to address the problem of natural and human-induced landslides in the region. However, it certainly needs improvement to be used in a more universal way.

Chapter 3

Living on landslides: land use on unstable slopes in a rural environment west of Lake Kivu (DR Congo)

"*We are the children of our landscape. It dictates behavior and even thought in the measure to which we are responsive to it.*"

- Lawrence George Durrell

3.1 Abstract

Landslides have been widely studied in terms of dangerous phenomena and land degradation processes, yet they may also be a source of opportunities for local communities in developing countries. However, little is known on the logics underlying land use in landslides. The aim of this study was to assess, the extent, modes of valorization and degree of satisfaction of famers exploiting landslides in the populated rural region of Kalehe on the rift flanks west of Lake Kivu (DR Congo). We interviewed 82 farmers living on 57 representative landslides; these movements being selected according to their characteristics (size, type), position along the hillslopes and accessibility or safety constraints. We show that almost all landslides are being exploited by farmers and that they adapt their land use to the type of landslide. Some types of landslides even offer more favorable conditions for cropping that land outside landslides. These contrasts in land use between landslides and the surrounding hillslopes are confirmed when looking at the whole region. Despite the perceived risk of landsliding, famers justify their settlement on unstable slopes by the immediacy of the benefits that outweigh the potential dangers. Better understanding the reasons for the settlement of rural populations on unstable slopes may help devise better risk mitigation strategies.

Keywords: land use in landslides, qualitative survey, perception assessment, tropical environment, DR Congo

3.2 Introduction

Landslides are a major natural hazard in mountainous regions around the world. The negative impacts of landslides are well documented, including loss of life, significant property damage, soil degradation and sedimentation of rivers (Garwood et al., 1979; Petley, 2012; Dowling and Santi, 2014; Clark et al., 2016; Haque et al., 2016; Froude and Petley, 2018; Li et al., 2022). Yet, despite their negative impacts, they can also be a source of opportunity for people living on them or in their vicinity. This is because landslides can modify land characteristics such as topography, soil moisture or soil type in such a way as to provide for new opportunities. For example, on Mount Elgon on the Uganda-Kenya border, Van Eynde et al. (2017) showed that landslides older than 60 years have a higher organic matter content than on adjacent land. Changes in land characteristics within landslides can be generative of biodiversity (Alexandrowicz and Margielewski, 2010; Temme, 2021) or induce alternative land uses (Walker and Shiels, 2013). For instance, the flatness of large landslides could provide favourable topography for infrastructure development or even for establishing entire villages in mountainous regions (Hewitt, 2010). Landslides can also lead to the outcrop of exploitable materials or minerals, as observed for instance in the Kivu region of DR Congo (Maki Mateso et al., 2023). For an area in the Outer Carpathians in Poland, Kroh (2017) reported that the proportion of forest was 11% higher, and the proportion of cropland 3% lower, in landslides compared to areas outside landslides. However, apart from the latter study, the way landslides are being exploited and the factors influencing this exploitation have not been studied in detail to date, unlike the processes of spontaneous recolonization of landslides by vegetation (e.g., Walker and Shiels 2013; Hu et al., 2018; Nakileza and Tushabe, 2018).

Tropical mountainous regions are particularly susceptible to landslides (Stanley and Kirschbaum, 2017; Broeckx et al., 2018; Dewitte et al., 2022). In these regions, studies have mainly focused on the role of natural factors (e.g., rainfall, soil weathering) and of (changes in) land use patterns in landslide occurrence (e.g., Guns and Vanacker, 2012; Depicker et al., 2020). Additional studies have also addressed the direct impacts of landslides as well as the perception of causes and risks in order to improve awareness and management of landsliding and the resilience of population to this type of disaster(Misanya and Øyhus, 2015; Alcántara-Ayala and Moreno, 2016; Mertens et al., 2016; Masaba et al., 2017; Mertens et al., 2018; Pham et al., 2019). However, because conditions in tropical mountainous areas are often more favourable than in tropical lowlands in terms of climate, soil types or sanitary pressure, these regions are commonly densely inhabited (Nyssen et al. 2009; Eze et al. 2021). As a result of the high land pressure, every piece of land counts, event those that are located on landslides (Mertens and Vranken, 2018).

The present study therefore aims to understand the logics underlying land use in landslide affected landscapes in rural areas in tropical mountainous regions. To do that, we focus on the populated Rift flanks west of Lake Kivu in DR Congo which is subject to numerous landslide processes of varying ages and sizes (e.g. Maki Mateso et al., 2023). Specifically, the objectives were to: (1) assess knowledge of landslides and perception of landsliding risk by farmers as a function of landslide characteristics, (2) assess whether landslide characteristics condition the perception of the land value and the degree of satisfaction at exploiting land located in landslides, (3) determine the types and extent of land use in landslide-affected landscapes.

3.3 Materials and methods

3.3.1 Study area

The study was conducted in a rural mountainous setting in the Kalehe territory of South Kivu, eastern DR Congo (Fig. 3.1). The lithology is made of two types of Mesoproterozoic rocks (1600- 1000 Ma), namely detrital rocks (pelites and quartzopelites) and younger (1375-980 Ma) granitic rocks (mica and leuco-granites) (Fig. 3.1a; Laghmouch et al., 2018). Sixty years ago, more than 70% of the mountain flanks were covered by forest (Fig. 3.1c). Currently, a few relic patches of forest remain (~ 5%) and, in rare places, the forest has been replanted (~ 3%) (Fig. 3.1c). The large elevation differences (> 1200 m) between the east and the west of the area induces orographic climatic conditions that impact on the vegetation cover and on the land use. Indeed, from the lake shore (approx. 1460 m a.s.l.) to about 1700 m elevation, there used to be a mesophilic forest with dense undergrowth, but almost all of it has been converted into agricultural land (Lebrun 1960; Nzabandora 2016). A transition zone existed between 1700 m and 1900 m elevation with a mixture of species from the lower and upper zones (Nzabandora, 2016). Between 1900 m and 2600 m elevation, mountain rainforest with an abundance of epiphytes were found and, further up, the high mountain forest with *Podocarpus* (Lebrun 1960; Nzabandora 2016). In this high-elevation zone, a few forest relics still exist today despite widespread conversion to cropland and pasture.

The population density of the Kalehe region has grown significantly over the past decades, currently reaching ± 200 inhabitants/km² (European Commission and Joint Research Centre (JRC), 2015). The highest densities are found in the downstream part of the area, close to Lake Kivu, notably because of the opportunities for commercial exchanges through its connection to the major road axis 'La Nationale n°2' and to Lake Kivu. Moreover, the demography in this part of the study area has also increased over the last few decades due to the influx of households deserting the heights as a result of the insecurity in the region. Although less populated, the cooler and more humid mountain ridges offer opportunities for year-round cultivation and grazing.

The main source of income for the people of Kalehe in this rural mountainous environment is agriculture (Ciza et al., 2021). The demand for agricultural land is still pressing given the high population pressure in the area (Depicker et al., 2021). Despite the potential risks, many landslides are thus being put to agricultural use. In addition, the flat areas present in large landslides are valued for house construction. The stone blocks and sand mobilized by landslides can also be used as building materials or as a source of income.

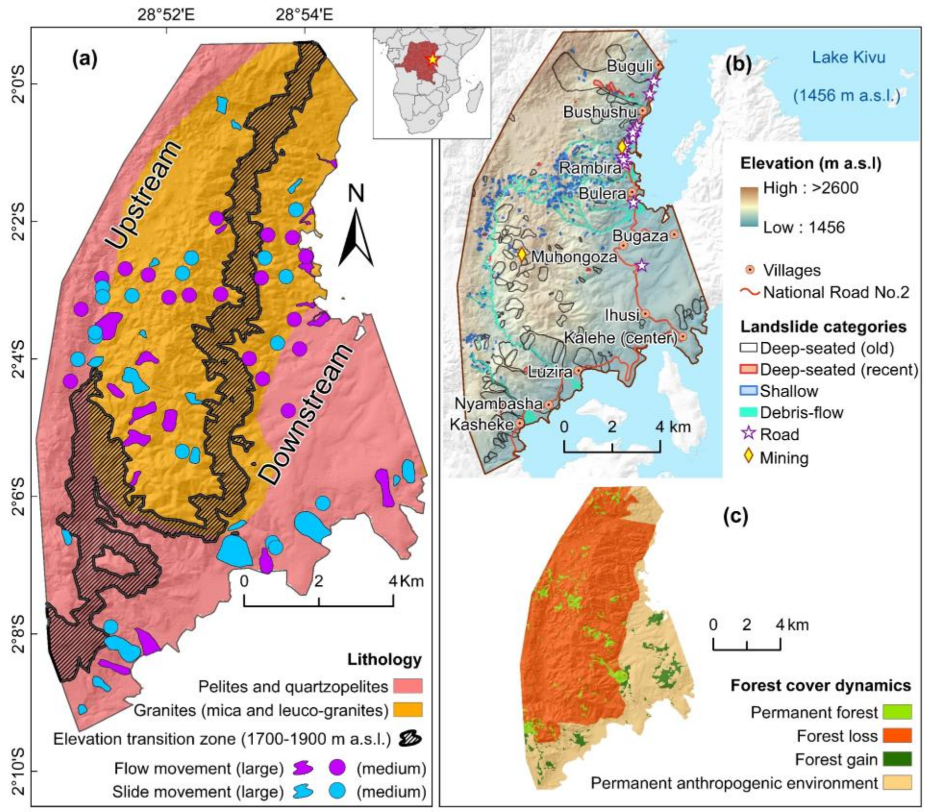


Figure 3. 1: *(a) Lithological setting (Laghmouch et al., 2018), and selected landslides as a function of size, movement and topographic position (downstream: < 1700 m; transition zone: 1700 m to 1900 m; upstream: > 1900 m a.m.s.l) (see section 3.2.2. regarding the three stratification criteria). Selected landslides smaller than 1 ha are represented by a circle. (b) Comprehensive landslide inventory in the*

region of Kalehe (inventory compiled by (Maki Mateso et al., 2023). (c) Forest cover dynamics between 1955-58 and 2016 (Maki Mateso et al., 2023).

3.3.2 *Landslide sampling*

The target study area has a high susceptibility to landslides with 785 inventoried landslides ranging from ancient to very recent mass movements (Fig. 3.1b; Maki Mateso et al., 2023). The largest landslides are clearly old features that are major shaping element of the landscape (Dewitte et al., 2021) whereas the smallest landslides are at most a few years old. Amongst the recent landslides, many were triggered in October 2014 by an intense convective rainfall event (Maki Mateso et al., 2023).

From the existing inventory, a selection was made by stratified sampling (Kothari, 2004; Fig. 3.1a). Three stratification criteria were considered because of their presumed impact on land use potentialities in landslide: size, topographic position and type of movement (Table 3.1). Regarding landslide size, it was expected that the apparent stability of some parts of large landslides would lower the perceived risk of landsliding, which in turn might favour their use as compared to smaller landslides. Also, on large landslides, more diverse topographic conditions may induce a greater diversity in land uses compared to medium-sized landslides. Two size classes were considered. The first size class (medium) is between 0.1 and 1 ha (n = 256), which is equivalent to the average size of individual farmer fields (Ndjadi et al., 2020). The second size class (large) is between 5 and 100 ha (n = 64) and would a priori be exploited by several people given the size of the farms in the region. Landslides with intermediate sizes between 1 and 5 ha (n = 98) were excluded from the selection to ensure that in the analysis the differentiation between the two selected size classes is robust. In addition, landslides < 0.1 ha (n = 364) were excluded because they are difficult to analyze due to rapid vegetation regrowth. Those > 100 ha (n = 3) were also excluded from the sample because it is likely that people living on them have difficulty imagining that they live in a landslide.

Regarding topographic position, two classes were considered based on the natural ecological distribution of plant species (Lebrun, 1960; Nzabandora, 2016): landslides located at an elevation < 1700 m ("downstream") or > 1900 m a.s.l. ("upstream") (Fig. 3.1a). This stratification criterion was selected because it was hypothesized that the orographic climatic conditions, related to altitude, could induce differentiated land uses in landslides. In addition, the differences in land pressure (higher population density at lower elevation) and in access to communication routes (greater accessibility in the downstream area) could also induce differentiated land uses. The landslides (n= 48) located in the transition zone (1700-1900 m) were excluded.

The third stratification criterion is the type of movement of the landslide materials, i.e. the slide or flow type (Fig. 3.1a). Slides are characterized by a relatively slow movement as compared to flows (Hungr et al., 2014). In addition, their displaced mass is impacted by limited internal deformation, i.e., slides display structures and units that are relatively homogenous, commonly separated by secondary scarps. The slides have a prominent main scarp, and, when driven by rotational movements, have a back-tilted landslide head that is relatively flat (Hungr et al., 2014). Flows are much less structured and their topographic signature is far less pronounced (Hungr et al., 2014). This could affect the opportunities for land use, in particular with respect to the structure of the soil profile.

In the end, out of the 785 landslides present in the initial inventory, 513 were excluded due to either their size or topographic position. The actual study focused on 70 landslides selected from the remaining 272 landslides. This number was guided by what could reasonably (in terms of time and access) and safely (given the high insecurity in the region) be surveyed in the region, while ensuring a number of landslides (8 to 9) that was deemed a priori sufficient for each combination of size-topographic position-movement. For each combination of size, topographic position and landslide movement, and , 8-9 landslides were randomly selected (Table 3.1).

In addition to the three stratification criteria, each landslide was characterized according to age, depth and lithology. Regarding age, 'old' (> 60 years) or 'recent' (< 60 years) landslides were distinguished on the basis of their presence/absence on aerial photographs dating from 1955-58 (Maki Mateso et al., 2023). In terms of depth, landslides were characterized as deep-seated or shallow (see Fig. 3.2, Maki Mateso et al., 2023); shallow landslides being defined here as having a depth of the surface of rupture < 5m (Maki Mateso et al., 2023). Finally, the lithology on which the landslides occur was recorded (Laghmouch et al., 2018).

Table 3- 1: *Total number of landslides in the initial inventory for each combination of size, topographic position and type of movement (= total landslides), and number of landslides selected through stratified sampling (= Selected landslides). The numbers in parentheses refer to the actual number of landslides surveyed, which may differ from the originally planned number (see text for explanation). For each combination, the number of surveyed persons is also indicated.*

Movement	**Size**	**Downstream position (< 1700 m)**			**Upstream position (> 1900 m)**		
		Total landslides	Selected landslides	Surveyed people	Total landslides	Selected landslides	Surveyed people
Flow	**Large** (5 – 100 ha)	10	9 (9)	19	11	8 (5)	9
	Medium (0.1 – 1 ha)	14	9 (5)	5	154	9 (9)	9
Slide	**Large** (5 – 100 ha)	16	9 (7)	13	33	9 (6)	9
	Medium (0.1 – 1 ha)	12	8 (8)	10	22	9 (8)	8
	Total	52	35 (29)	47	220	35 (28)	35

3.3.3 Survey questionnaire

Data collection was based on field surveys conducted using a questionnaire (**Appendix Table B.7**) in local languages (Swahili and Kihavu). The survey was conducted among people living or working on the landslides during the period from mid-July to the end of August 2019 (Table 3.1). The average time to submit a questionnaire was 45 minutes. The questions covered four topics, namely (1) knowledge and perception of risks related to land use in landslides, (2) land value and motivations for land use in landslides, (3) satisfaction at using land in landslide, and (4) differences in land use inside and outside landslides. Finally, we collected basic data on the socio-professional and economic identity of the farmers, plots size, etc.

In addition to landslide characteristics (size, topographic position, type of movement, age, depth, and lithology), natural conditions (e.g, slope steepness, soil characteristics) must be considered to explain land use in landslide. The respondents were asked to assess these natural conditions on the landslides during the interviews by comparison with the hillslope adjacent to the landslide. Thus, each respondent was asked to compare the plot he/she was exploiting in the landslide to land adjacent to the landslide in terms of slope gradient (less steep, equal or steeper), soil fertility (lower, equal or higher), oil depth (shallower, equal or deeper), soil moisture (drier, equal wetness or wetter), stoniness (less, equal or more) and sand content (less, equal or more).

Land uses and the choice of crops may depend on landslide characteristics and natural conditions in the landslides. Free-form sketches were used, with the help of each farmer, to record the land use patterns within each landslide area as a function of the natural conditions. A summary sketch was then drawn up to illustrate the land use patterns in landslides, considering what the respondents said and our personal observations in the field.

3.3.4 Regional land use study

Land uses documented by means of the farmer surveys are restricted to the farmers' fields, i.e., they do not necessarily encompass the entire landslides especially for the large ones. Consequently, a comparative study of the different types of land use inside and outside the landslides was carried out based on a supervised classification (using Envi software, version 4.8) of land uses from a November 2014 Pléiades image at very high spatial resolution (2 m). This image was the source of information closest in time to the field survey period available at this resolution.

The heterogeneity of rural landscapes in sub-Saharan Africa makes it difficult to extract land use classes using remote sensing (Eggen et al., 2016; Kassawmar et al., 2018; Forget et al., 2018). Our study area is characterized by this complexity of land use, especially due to plots comprising several crops at different stages of development and with highly variable plant densities, the presence of different types of trees and shrubs within the plots, soils of different colors, etc. The very high spatial resolution of the Pléiades image and a good knowledge of the terrain were an asset in defining the land use classes. For each land use class, we defined numerous calibration and validation areas using polygons to ensure that they were representative of all spectral variations within a given land use class. Thus, the number of polygons/pixels that were used for each land use class for calibration and validation purposes were respectively : crops (subsistence + vegetable crops) (cal: 100/4094; val: 47/3015), forest (cal: 17/382; val :7/422), banana plants (cal: 21/651; val: 10/516), eucalyptus (cal: 70/1596; val: 45/1340), pasture (cal: 24/4924; val: 23/3262); built and bare area (cal: 94/1851; val: 67/1878); lake (cal: 13/1469; val: 11/1128) and cloud covers (cal: 7/2354; val: 4/1526). The quality of the supervised classification was assessed by means of the Overall Accuracy and Kappa coefficient values (Vibhute et al., 2016; Aziz and Alwan, 2021).

The spatial analysis of land use inside and outside landslides focused on the 70 selected landslides (Table 3.1). For each landslide, land use analysis was applied to two distinct zones (**Appendix Figure B1**): 1) the interior of the landslide; an interior buffer of 10 m was defined to minimize the risk of mixel that would include land uses that are outside the landslides, and 2) the exterior of the landslide, i.e., adjacent lands, comprising an area between 50 and 300 m around the landslide after excluding any other landslides located in this area. Based on our field observations, a 50-m buffer zone was applied around each landslide in order to exclude land uses developed in the landslides that would extend outward. For the analysis the different land uses inside and outside landslides were compared in terms of their proportions. According to the stratified classification, the analyzed areas inside and outside the landslides are presented in **Appendix Table B1**.

3.3.5 Data analysis

The survey and spatial analysis data were compiled and analyzed using IBM SPSS Statistics (Version 26) software (see **Appendix Table B2** summarizes the different tests applied, their meaning, the formula and common uses). In addition to descriptive statistics including frequency distributions and graphs (George and Mallery, 2019) non-parametric correlation analysis (Spearman's rank correlation coefficient rho; $-1 \leq rho \leq 1$; see **Appendix Table B.3**) was used to identify potential relationships between the landslide characteristics (size, topographic position, movement, age, depth, and lithology). Values close to 1 or -1 indicate a strong relationship between two variables, while values close to 0 express the lack of correlation.

Chi-square tests (George and Mallery, 2019) were used to assess the dependence between landslide characteristics (size, topographic position, movement, age, depth, and lithology) and (1) perceived landsliding risk, (2) natural conditions in the landslides (slope and soil characteristics), (3) land use choices, (4) farmers' level of satisfaction at exploiting a plot in a landslide. Chi-square tests (George and Mallery, 2019) were used to assess the dependence between the number of farmers practicing a given land use and the location (inside or outside landslides).

Farmers' satisfaction with using land inside landslides may be related to the natural conditions in the landslide. Multiple correspondence analysis (MCA; Murtagh, 2007; Abdi and Williams, 2010) was applied to determine the correspondence between the farmer levels of satisfaction (unsatisfied, little satisfied, moderately satisfied and very satisfied) and the natural conditions (slope, soil characteristics) present on the landslides on which they operate. In the spatial analysis, parametric Student's t tests or, failing that, the non-parametric Wilcoxon test of comparison of 2 paired means (George and Mallery, 2019) were applied to determine if there is a difference in the proportions for each land use inside and outside the landslides.

Multiple linear regression, which also assesses variance (ANOVA), was used to assess whether landslide characteristics (two level independent categorical variables: medium or large size, flow or slide type, ...) explain the differences in proportion (continuous dependent variable) of a given land use class between the landslide interior and exterior (Papke and Wooldridge, 1996; Baum, 2008). The land use classes considered are crops (subsistence + vegetable), forest, banana plants, eucalyptus, and pasture. When modelling a dependent variable that is in the form of a (difference in) proportion, the bounded nature of the variable must be taken into account, as the use of a proportion in a linear regression model will generally give nonsensical predictions for extreme values (Baum, 2008). The dependent variable (differences in proportion of each land use between the landslide interior and exterior) was therefore logit transformed as follows (Baum, 2008; Orsini and Bottai, 2011) : (1) normalizing the difference in proportions to an interval [-1,1] ('$Diff\_landuse_1$ '); (2) transforming the variable $Diff\_landuse_1$ to bring it into the interval [0,1] by means of

$Diff\_landuse_2 = Diff\_landuse_1 * 0{,}5 + 0{,}5$; (3) transforming this variable back to the interval [-∞,+∞] by applying $Diff\_landuse_3 = \log(Diff\_landuse_2 / (1 - Diff\_landuse_2))$. It was verified that the selected independent variables did not pose multicollinearity problems (Variance Inflation Factor < 2).

3.4 Results

3.4.1 Landslide sampling and characteristics of surveyed farmers

Of the 70 landslides selected by means of the stratified sampling (Fig. 3.1a), 57 landslides ended up being surveyed (Table 3.1). The remaining 13 landslides were not surveyed for reasons of unavailability of farmers (n=4) or safety concerns (n=6), or because the landslide was not exploited due to recent landslide activity (bare ground or totally covered by stones; n=3). The latter were all flow type, medium-size landslides located in the downstream zone. The very poor safety conditions in the region did not allow us to complement the dataset with additional landslides.

For the 57 landslides surveyed, 82 farmers were interviewed (Table 3.1). In terms of socio-economic status, 60% (n=49) of the 82 farmers interviewed had no formal education, 38% (n=31) had primary-secondary school education, and 2% (n=2) had university education. All of them were involved in agriculture, but some farmers derived their income from one or more additional activities. Overall, 77% (n=63) lived mainly from subsistence farming, 11% (n=9) were mainly involved in informal trade, 9% (n=7) were teachers in primary or secondary schools and 3% (n=3) were fishermen. Labour on the farms was mainly family-based. The average number of children per household was eight. The average size of the respondents' farms was 1.9±1.6 ha (mean ± standard deviation) divided among 3 plots on average. The plots located on the landslide represented on average 37% (0.7±0.6 ha) of the total farm acreage.

3.4.2 Knowledge of landslides and risk perceptions

All respondents said they knew what landslides are and that they had already observed one. In fact, 74% (n=61) of the respondents stated that they lived on an active landslide. To support this, they reported the following phenomena: ground deformation (71%), flooding (46%), rock falls (49%), tilting of trees (30%) or cracks in the walls of buildings (8%). All respondents were able to mention one or more causes for the occurrence of a landslide. The main causes cited were heavy rainfall (60% of respondents), deforestation (13%) and earthquakes (11%). The second (43%) and third (24%) most frequently cited causes were earth displacement during construction works or terracing between agricultural plots and the removal of stone blocks as building material or to conquer arable land.

Of the 82 respondents, one third (n=27) had started farming their plot (currently located inside a landslide) before the landslide occurred. Of the remaining two thirds, 23 respondents were aware that they had settled on a landslide, while 32 were unaware of the landslide at the time of settlement. At the time of the survey, 76% (n=62) of the surveyed farmers were aware that they were operating on a landslide. The remaining 24% (n=20), who were not aware of being on a landslide at the time of the survey, had all settled on their plot after the occurrence of the landslides. Eighty-five percent (n=17) of them were located on old deep-seated and large landslides. The remaining 15% (n=3) settled on recent shallow landslides where vegetation cover had already hidden some of the signs of landsliding.

The length of time the respondents had been operating on landslides provides an indication of their experience with managing such sites. Of those who settled after the occurrence of the landslides, 69% had more than 10 years of experience on the site. And of those who arrived before the landslides occurred, 89% had been there for more than 10 years. For farmers who settled after the occurrence of landslides and with full awareness (n = 23), the main motivations to farm a landslide were (more than one answer possible): a perceived better productivity of the soil (52%), the advantageous cost of land (48%), the attractive rental price (sharecropping) (30%), and the wish to keep the land in the family or customary circle following an inheritance (17%). Four percent of respondents had acquired the land for free through non-governmental organizations (NGOs) or local notables.

Regarding the perception of landslide risk, 4%, 35%, 48% and 13% of the 82 respondents reported that at the time of their settlement, they perceived the risk as nil, low, high, and very high, respectively based on the elements at risk on their plots (house, crops field, pasture, etc.). At the time of the survey, 2%, 21%, 29% and 38% of the 82 respondents perceived the landslide risk as nil, low, high, and very high, respectively. The two (~2%) non-risk-aware farmers were located near the center of large and old landslides, which likely explains their lack of risk perception. If we limit ourselves to the 62 respondents who were aware of living on a landslide at the time of the survey, 0%, 11%, 42% and 47% perceived the landslide risk as nil, low, high, and very high, respectively. For these 62 farmers, Chi-square analysis indicates that the risk assessment does not differ significantly according to landslide characteristics (data not shown).

Farmers also reported the elements at risk of landsliding on their land and the level of damage suffered. Subsistence crops were most frequently affected by damage (n=66: **Appendix Figure B.2**). Regarding the perceived damage level, buildings and subsistence crops suffer the most severe damage, followed by vegetable crops and quarries (based on high and very high levels; **see Appendix Figure B.2**). Forestry appears to be the least affected by landslide damage (less vulnerable).

3.4.3 Land value inside landslides and farmer satisfaction

The economic value of land inside landslides can be higher (n = 39), similar (n = 13), or lower (n = 30) than land adjacent to the landslide.

The 39 farmers who rated the value of their plots higher than land adjacent to the landslide justified this by (1) their perception of soil characteristics: more fertile (90%), deeper (21%), wetter (44%) soils, with a low proportion of stone and sand (13%); (2) the topography: lower slopes (64%) and less unstable (15%); (3) the possibility of year-round cultivation (26%), and (4) the presence of soil conditions favourable for growing banana plants (23%). On the contrary, the 30 farmers who considered the value of their plots to be lower than land adjacent to the landslide attributed this to a steeper slope (53%), less fertile soils (43%), shallower soils (27%), less moisture (7%) and a greater abundance of sand or stones (53%).

The natural conditions listed by farmers as affecting land value are conditioned to varying degrees by landslide characteristics (see p-values < 0.05 of Chi-Square tests in Table 3.2 showing significant dependencies among variables; these dependencies are discussed in detail in Section 3.4.2). Note that these landslide characteristics are correlated among each other to a varying extent **(Appendix Table B.3**). Age and depth are most strongly (positively) correlated. Weaker but still very significant positive correlations are observed between age and movement, age and size, movement and depth, and size and depth. The three landslide stratification criteria (size, position, type of movement) were not significantly correlated (as expected given the sampling procedure), nor were there significant correlations between lithology and other criteria **(Appendix Table B.3**).

Table 3- 2: *Relationships between landslide characteristics and natural conditions of farmers' plots inside the landslide. The natural conditions were evaluated by the surveyed farmers relative to the land adjacent to the landslide. P-values of the Chi-Square tests in bold represent statistically significant differences at the 0.05 level.*

		Landslide size			**Landslide location**			**Landslide movement**			**Landslide age**			**Landslide depth**			**Lithology**		
		Medium	**Large**	**Total**	**Downstream**	**Upstream**	**Total**	**Flow**	**Slide**	**Total**	**Recent**	**Old**	**Total**	**Shallow**	**Deep-seated**	**Total**	**Pelites**	**Granites**	**Total**
Natural conditions		**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
Slope	Steeper	50	18	31	26	37	31	41	17	31	58	9	31	53	16	31	13	46	31
	Equal	28	32	31	28	34	31	26	36	31	25	35	31	19	38	31	34	27	31
	Lower	22	50	38	47	29	39	33	47	39	17	57	39	28	46	39	53	27	39
Total		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
p-value of Chi-Square tests				**0.005**			0.236			**0.029**			**< 0.001**			**0.002**			**0.005**
Fertility	Lower	56	16	32	26	40	32	33	31	32	44	22	32	50	20	32	18	43	32
	Equal	38	32	34	47	17	34	35	33	34	31	37	34	34	34	34	34	34	34
	Higher	6	52	34	28	43	34	33	36	34	25	41	34	16	46	34	47	23	34
Total		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
p-value of Chi-Square tests				**< 0.001**			**0.02**			0.946			**0.026**			**0.004**			**0.023**
Soil depth	Shallower	53	10	27	23	31	27	35	17	27	39	17	27	47	14	27	16	36	27
	Equal	34	38	37	47	23	37	35	39	37	39	35	37	38	36	37	26	46	37

	Deeper	13	52	37	30	46	37	30	44	37	22	48	37	16	50	37	58	18	37
Total		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
p-value of Chi-Square tests				**< 0.001**			0.081			0.161			**0.027**			**0.001**			**0.001**
Soil wetness	Lower	31	14	21	21	20	21	28	11	21	31	13	21	31	14	21	16	25	21
	Equal	50	30	38	38	37	38	35	42	38	44	33	38	44	34	38	24	50	38
	Higher	19	56	42	40	43	42	37	47	42	25	54	42	25	52	42	61	25	42
Total		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
p-value of Chi-Square tests				**0.003**			0.975			0.163			**0.019**			**0.035**			**0.005**
Stone content	Higher	50	36	42	47	34	42	44	39	42	58	28	42	53	34	42	26	55	42
	Equal	25	26	26	26	26	26	28	22	26	28	24	26	31	22	26	26	25	26
	Lower	25	38	33	28	40	33	28	39	33	14	48	33	16	44	33	47	21	33
Total		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
p-value of Chi-Square tests				0.381			0.43			0.582			**0.003**			**0.028**			**0.015**
Sand content	Higher	41	22	29	34	23	29	41	14	29	50	13	29	53	14	29	18	39	29
	Equal	22	26	24	26	23	24	24	25	24	22	26	24	22	26	24	24	25	24
	Lower	38	52	46	40	54	46	35	61	46	28	61	46	25	60	46	58	36	46
Total		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
p-value of Chi-Square tests				0.18			0.41			**0.01**			**0.001**			**0.01**			0.08

Among all the respondents, 24% said they were very satisfied, 32% moderately satisfied, 27% little satisfied, and 17% not at all satisfied with their land in the landslides. The degree of satisfaction is significantly conditioned by the size, age, and depth of the landslides, and by the lithology (see **Appendix Table B.4**). Overall, the perceived satisfaction is higher on large, old, deep-seated landslides and on those located on pelite bedrock.

The level of satisfaction of farmers also depends on the natural conditions inside the landslides. According to the respondents, good fertility, ease of tillage, and sufficient moisture in the soils over long periods of time are sources of satisfaction. Satisfaction is also high when landslide farming provides for food needs and allows for the sale of agricultural produce to meet family needs. On the contrary, landslides considered less fertile, difficult to work because of the presence of stones and presenting permanent instabilities are sources of dissatisfaction. The MCA synthesizes the link between the natural conditions inside landslides and the level of satisfaction (Fig. 3.2). Thus, (high) satisfaction is associated with farming of landslides that have wetter, deeper soil, and are more fertile than adjacent land, and to a lesser extent with landslides that are less sandy, less steep, and less stony. On the contrary, landslides that are less wet, less fertile, shallower, or more sandy than adjacent lands, and to a lesser extent more stony and present steeper slopes, result in dissatisfaction.

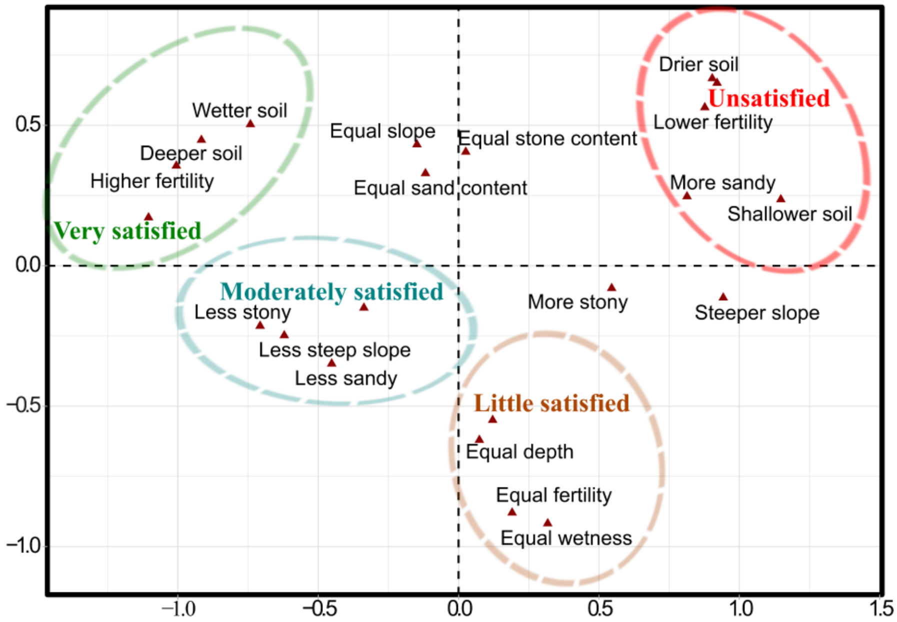


Figure 3.2: *Multiple correspondence analysis (MCA) of satisfaction levels with regard to the natural conditions present in the landslides compared to the land adjacent to the landslides. The groups surrounded by a dashed line are purely indicative. Colors from green to red are used to reflect the satisfaction scale from best to worst.*

3.4.4 Land use in landslide affected landscapes

All 57 landslides that were visited were being valorized in one way or another (**Appendix Figure B.3**). On 35% of the landslides, there were one or more houses. Other forms of valorization were subsistence crops (81%), vegetable crops (25%), banana cultivation (53%), forestry (51%), pasture and fallows (16%), coffee and fruit trees (19%), and building material exploitation (sand and stone quarries: 4%). Considering the 82 interviewed farmers, 32% had their homes located on the landslide, 79% grew subsistence crops, 21% grew vegetables, 48% grew banana plants, 10% grow coffee, 42% practiced forestry, 11% owned pastures, and 4% exploited building materials for sale.

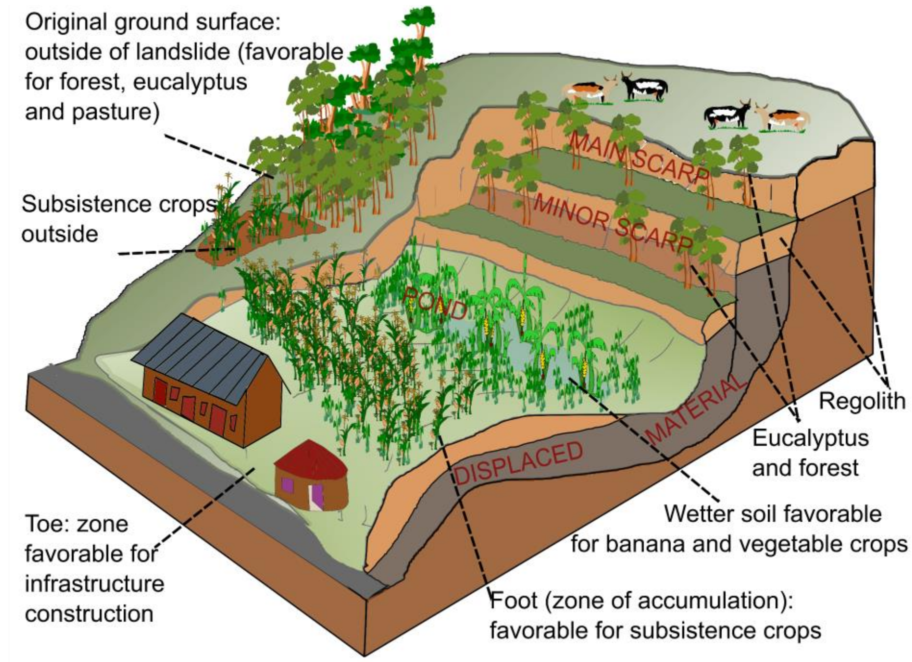


Figure 3. 3: *Schematic representation of land use in a landslide. This example mimics the main morphometric features of an old deep-seated slide.*

Based on field observations and survey results, it appears that topography is one of the main factors driving land use inside landslides (Fig. 3.3). Thus, the main and secondary escarpments, which are steeper and have drier soil, are devoted mainly to eucalyptus plantations, which also play a role in slope stabilizing according to the farmers. The concave area of the slope break, which is characterized by higher moisture, is dedicated to crops such as banana plants and market gardening. The convex zone (foot), characterized by medium humidity, is favourable to various subsistence crops. Homes and other infrastructure are preferentially built at the foot and toe of the landslide.

Based on the 65 farmers who own plots inside and outside a landslide, one can highlight significant differences for some forms of land use (Table 3.3). Banana cultivation and forestry are practiced preferentially on landslides, the former in pond zones and the latter on the steep slopes of escarpments. On the other hand, grazing land is preferentially located on the slopes adjacent to landslides.

Table 3-3: *Number of farmers who practice a given activity inside and outside landslides, based on the 65 interviewed farmers who own land both inside a landslide and elsewhere outside the landslide.*

	Inside landslide	Outside landslide	P-value Chi-square tests
Banana cropping	39	20	**0.04**
Subsistence cropping	65	54	0.61
Vegetable cropping	17	12	0.76
Tree plantation	34	7	**0.03**
Pasture	9	13	**0.02**
Coffee	10	9	0.87

Results further indicate that farmers adapt their choice of crops according to the characteristics of the landslide (Fig. 3.4). Thus, banana cultivation is proportionally more common on deep-seated landslides and those with a slide movement. Subsistence crops are preferred on old, deep-seated landslides, slide-type landslides, or landslides located on pelite bedrock. Vegetable crops are grown preferentially on large landslides, slide-type landslides or those on pelite bedrock. Finally, coffee cultivation is preferred on a landslide located over pelite bedrock. The results did not reveal a relationship between landslide characteristics and tree planting or pasture establishment (data not shown).

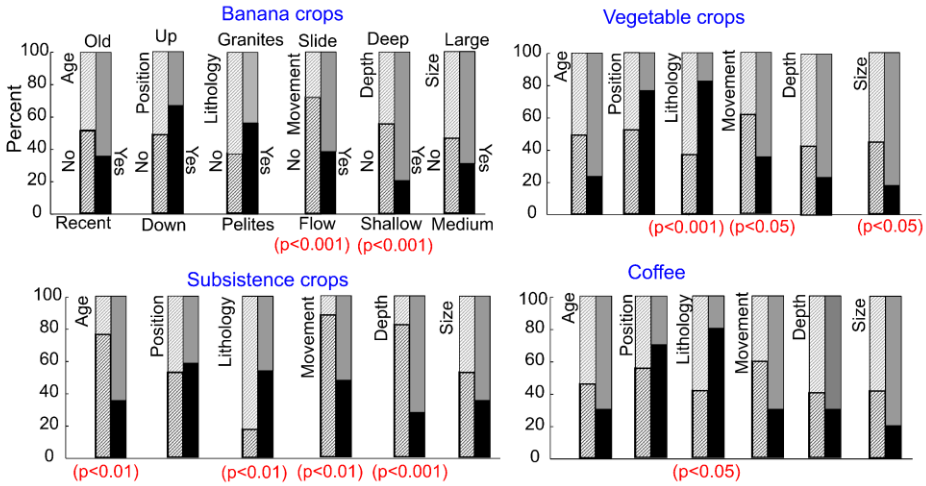


***Figure 3.4:** Influence of landslide characteristics on the cultivation of banana plants, vegetable crops, subsistence crops or coffee. For each characteristic, farmers are divided into two groups: those who do not grow the crop ('No', left) and those who do grow the crop ('Yes', right). Within each of these two groups separately, the proportion of farmers who are located on an old (top) or young (bottom) landslide, upstream or downstream, granites or pelites, etc. is determined. For example, for the 'age' criterion and subsistence crops, 24% of the farmers who do not grow food crops ('No') are located on old landslides (and thus 76% on recent landslides), while 64% of the farmers who grow food crops ('Yes') are located on old landslides (and thus 36% on young landslides). Chi-square test is used to compare two stacked bars in 100% choice (Yes or No) of a crop with regard to a landslide characteristic (see also **Appendix Table B.5 from which the Figure was derived**).*

Spatial analysis was performed on the 67 landslides that presented some form of valorization (**data extracted from Appendix Figure B.4**), after excluding the three landslides that are not exploited. No distinction could be made between subsistence crops and vegetable crops via the land use classification process. This analysis confirmed a differentiation in land uses on the landslides as compared to the adjacent land (Table 3.4). Crops occupy a larger proportion of the land area in the landslides than on the adjacent land. The proportion of land uses for forest, eucalyptus plantations and pasture are significantly higher on adjacent land than within landslides (Table 3.4). The proportion of banana plants is low given the importance of bananas in the local tradition (food, source of income, local beer, building material, soil fertilizer...), but this can largely be explained by their destruction by the bacterial wilt disease which started in 2001 (Ndungo et al., 2006; Blomme et al., 2017).

Table 3- 4: *Proportions (mean ± standard deviation) of different land uses on landslides and neighboring flanks (n = 67) and results of paired comparison tests.*

Land use	Inside landslide	Outside landslide	Paired comparison test		
	% of area	% of area	t or Z*	df	p-value
Crops (subsistence and vegetable)	69±24	55±22	3.93	66	**< 0.001**
Forest	9±11	14±13	-2.62		**< 0.01**
Banana plants	9±14	9±10	-1.41		0.16
Eucalyptus	2±4	5±7	-3.81		**< 0.001**
Pasture	11±13	17±18	-3.06		**< 0.01**

* Student t-test for Crops and Wilcoxon test (Z) for all other land uses

Landslide characteristics significantly explain the differences in proportions of crops, forest, banana plants and pasture between landslides and adjacent lands (Table 3.5). A summary of linear regression models (see **Appendix Table B.6**) show that: (1) for eucalyptus, no significant difference was found between the two zones; (2) the R^2 values of the regression models show that landslide characteristics explain the differences in crop, banana plants and forest proportions between landslides and adjacent land quite well and, to a lesser extent, for pasture.

***Table 3-5**: Land use proportions inside and outside landslide as a function of landslide characteristics and resulting difference in proportions. A positive difference means that the land use dominates inside the landslide; otherwise, the land use dominates on the adjacent land. Values in bold are landslide characteristics whose differences in proportions are significantly different according to the linear regression models (See **Appendix Table B.6** summary of linear regression models of differences in proportions (inside - outside) of different land uses inside and outside landslides according to landslide characteristics).*

	Position		Size		Movement		Age		Lithology	
	Downstream	Upstream	Medium	Large	Flow	Slide	Recent	Old	Pelites	Granites
Crop inside	0.65	0.73	0.74	0.64	0.79	0.59	0.82	0.56	0.61	0.73
Crop outside	0.54	0.56	0.51	0.59	0.52	0.58	0.51	0.59	0.47	0.60
Difference crops	0.10	0.17	0.23	0.05	**0.28***	**0.01***	**0.32***	**-0.03***	0.14	0.13
Forest inside	0.08	0.10	0.06	0.15	0.06	0.13	0.04	0.14	0.08	0.10
Forest outside	0.14	0.14	0.15	0.13	0.17	0.11	0.16	0.12	0.09	0.17
Difference forest	-0.06	-0.04	**-0.09***	**0.02***	**-0.11***	**0.02***	-0.12	0.02	-0.01	-0.07
Banana inside	0.13	0.05	0.09	0.11	0.03	0.14	0.01	0.17	0.17	0.05
Banana outside	0.14	0.04	0.08	0.10	0.08	0.10	0.06	0.12	0.14	0.06
Difference banana	-0.01	0.01	0.01	0.01	-0.04	0.04	**-0.05***	**0.05***	0.03	-0.02
Eucalyptus inside	0.03	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.02	0.03
Eucalyptus outside	0.06	0.04	0.05	0.04	0.06	0.04	0.05	0.04	0.05	0.05
Difference eucalyptus	-0.02	-0.03	-0.04	-0.01	-0.04	-0.01	-0.03	-0.02	-0.03	-0.02
Pasture inside	0.10	0.11	0.11	0.10	0.09	0.12	0.10	0.11	0.13	0.09
Pasture outside	0.12	0.22	0.21	0.14	0.18	0.17	0.22	0.13	0.25	0.13
Difference pasture	**-0.02***	**-0.11***	-0.10	-0.03	-0.08	-0.05	-0.12	-0.02	**-0.13***	**-0.03***

Reference modalities for predictors are: position = downstream; size = medium; movement = flow; age = recent; lithology = pelites (p-value: * < 0.05, ** < 0.01, ***< 0.001).

3.5 Discussion

3.5.1 Landslide knowledge and constraint/opportunity for land use in landslide

Out of the 70 landslides considered in this study, only three were not being exploited. This reflects the strong demographic pressure in the region and the resulting difficulty to access agricultural land (Heri-Kazi and Bielders 2021). Indeed, land pressure is a recurrent problem in tropical mountainous areas, which often leads to exploitation of marginal lands (Nyssen et al. 2009; Eze et al. 2021) or, as in the present case, to the exploitation of landslides in spite of the potential risks incurred by crops, forestry activities or infrastructure.

The vast majority of respondents (62) actually declared living on an active landslide, something they could support by listing one or more signs of landslide activity. Not surprisingly, most of these respondents (89% of 62, n=55) rated the risk of damage due to landsliding as high to very high. As a matter of fact, about one third (33%) of the farmers experienced landsliding on their land (see **Appendix Figure B.3c to g**). Yet all of these farmers have chosen to keep exploiting the landslides in spite of the potential risks. While some farmers may settle or stay on the landslides for lack of available land or livelihood opportunities elsewhere, or to keep the land within the family following an inheritance, the study also reveals that there may be potential benefits associated with the exploitation of landslides that compensate for the perceived landsliding risk. These benefits may derive from the perception of a greater productivity of the land (see further), flatter land (near the toe of the landslide) where houses can be built more easily, or extractive activities (stone or sand quarries). This is in line with the study of Hewitt (2010) in the Himalaya mountains which showed that, despite the risk, landslides can be a source of opportunities arable land, settlement of villages) for mountain populations. Certain natural conditions (higher moisture, greater fertility, deeper soils, gentler slopes, fewer stones or less sand) within a landslide favor valorization and may arguably reduce the perception of risk. For some farmers, however, the main motivation does not lie in the productivity but rather in the lower cost of land or lower rental price.

Though a majority of farmers were aware of exploiting land on a landslide, about ¼ (20 out of 82) were not aware of it at the time of the survey. Eighty-five percent of the latter were exploiting old, large and deep-seated landslides. The low perception of risk in old, large, and deep-seated landslides should, however, be put into perspective. In general, these landslides are slow-moving and rarely cause casualties. Nevertheless, since their slow movement can manifest in the long-term, they can lead to pervasive damage to infrastructure (Lacroix et al., 2020). Sometimes these landslides undergo runaway acceleration for reasons that remain poorly understood (Handwerger et al., 2019) causing widespread destruction and casualties (Iverson et al., 2015 ; Lacroix et al., 2020). The increasing anthropic pressure may amplify the landslide dynamics and makes the populations more and more vulnerable (Dille et al., 2022). In our rural context, where anthropic pressure is growing, in particular through new constructions and the expansion of agricultural land, there is an increased chance of localized reactivations that are harmful to the exposed populations (Mugaruka Bibentyo et al., 2017). There may therefore be scope for raising the risk awareness of people regarding this type of landslide.

3.5.2 *Land value in landslides*

Nearly 80% of all farmers had experience in managing plots both inside and outside the landslides, and 70% of them had more than 10 years of experience. They were therefore able to provide a credible assessment of the value of land inside landslides as compared to land adjacent to the landslides. The study reveals that the value of land inside landslides (and likewise farmer satisfaction) may be higher, similar or lower than land adjacent to the landslides, and that this depends on the natural conditions in the landslide. Unsurprisingly, greater fertility, lower slopes, fewer stones, lower sand content, deeper and moister soils are a source of satisfaction. Even though these natural conditions can be quite variable within a given landslide (see further), it was shown that they are in first instance related to the landslide characteristics.

Natural soil fertility is particularly important for small-holder farmers of the South Kivu region because they have access to very little or no organic amendments and can hardly afford mineral fertilizers to enrich their soil (Pypers et al., 2011; Munyahali et al., 2017; Heri-Kazi and Bielders, 2021). Fertility is usually appreciated by small-holder farmers on the basis of productivity, which in turn depends on numerous factors among which soil chemical (e.g., pH, nutrient availability, soil organic matter content) and physical properties (e.g., soil depth, moisture, stoniness, soil texture). Fertility inside the landslides (as appreciated by farmers) appears to be significantly better than outside for landslides that are old, deep-seated, large or located on pelite rocks (Table 3.2). It is lower than outside for landslides that are recent, shallow, medium or located on granite. The lower fertility in recent landslides (which are also predominantly shallow and medium; **Appendix Table B.3**) may result from reduced soil thickness but also from the perturbation of the soil profile and in particular from the low organic matter content in the topsoil as a consequence of mixing during landsliding (Temme, 2021). Organic matter content plays a central role in soil fertility, particularly in smallholder farming systems (Tiessen et al., 1994). In similar environments, Lundgren (1978) in Tanzania and Van Eynde et al. (2017) in Kenya and Uganda both reported lower soil organic matter contents in recent landslides compared to adjacent land. Higher fertility in old landslides compared to adjacent land may then result from the greater soil depth (Table 3.2), but also from the recovery of the soil structure and soil profile and in particular of the organic A horizon. For landslides on Mount Elgon (Kenya/Uganda), Van Eynde et al. (2017) showed that organic matter content in the topsoil recovered to its original levels after approx. 60 years and may even exceed the original levels for older landslides, which was hypothesized to result from colluvial deposits in environments with high erosion rates, larger biomass restitutions as a result of the increased productivity, and possibly slower organic matter decay in areas of excess moisture accumulation within the landslides.

For landslides located downstream, fertility is predominantly similar inside and outside the landslide, but for upstream landslides, both higher and lower fertility are observed in almost equal proportions. Lower fertility landslides appear related to the landslides triggered in October 2014 (Maki Mateso et al., 2023). The higher fertility inside upstream landslides could be because these lands are suited for crops while the outside is devoted to other land uses such as pasture. The perceived equal fertility between the landslide and adjacent lands in the downstream zone (Table 3.2) could be explained by the fact that: (1) year-round land use in the landslide would make the fertility level equivalent with adjacent flanks where farming practices depend on agricultural seasons; (2) the high demand for agricultural land in this zone causes the inside and outside soils to have the same level of soil exhaustion. With respect to lithology, the better fertility inside landslides on pelites compared to adjacent flanks could be justified by two facts: (1) these landslides are predominantly older and the soil has had time to reconstitute itself with the availability of soil minerals that were at depth brought to the surface during landslide triggers, (2) inside these landslides, the flat topography of the transport and accumulation zones would favour the preservation of organic matter; whereas on the adjacent flanks, the steeper slope favours soil erosion carrying the organic matter downhill. However, the soil profiles studied on the pelites, while not necessarily on a landslide, are clayey and were found to contain good organic matter levels (Pecrot and Leonard, 1960; Munyahali, 2018). With respect to granites, the study does not show a difference in fertility between inside and outside landslides: (1) in general, soils developed on the granites would be less fertile, as they have a lower proportion of nutrients through their sandy texture and acidity, as observed in nearby Rwanda (Pecrot and Leonard, 1960; CIALCA, 2008; Muliele Muku, 2014); (2) landslides on the granites are, for the most part, recent and shallow, and their soils have not yet had time to recover.

Higher perceived soil moisture compared to the adjacent land is associated with landslides that are old, deep-seated, large or located on pelites (Table 3.2). These landslides commonly present a hummocky topography that results from back-tilted blocks, different moving units, a succession of secondary escarpments and different phases of displacements during their lifespan (Alexandrowicz and Margielewski, 2010; Schlögel et al., 2015; Dille et al., 2019). In such irregular topographic settings, wetlands and ponds can develop. For farmers, these zones of higher humidity are a source of opportunity, as they allow the cultivation of moisture-friendly perennial crops (such banana plants) and some subsistence crops, even outside the usual cropping seasons. The fact that soils are perceived as wetter on pelites than on granites may be related to their more clayey nature (Pecrot and Leonard, 1960; Munyahali, 2018) which retains water better in the soils and slows down internal drainage. The sandy-clay soils on the granites are more permeable because of their texture (Pecrot and Leonard, 1960).

The appreciation of soil depth is probably difficult for the farmers and interpretation of the results regarding this variable may require special caution. Nevertheless, the occurrence of deeper soils within old, deep-seated, large landslides and on pelite rocks as compared to adjacent land can originate from the loose material displaced through the landslide formation and accumulated in the deposit area (Di Maio et al., 2018). In addition, as in adjacent land, with increasing age of the landslide, the accumulation of litter from the biomass of various crops and plants will increase the thickness of the topsoil A-horizon while soil weathering may increase the thickness of the profile as a whole (Wilcke et al., 2003; Elias and Dias, 2009). Furthermore, soil

depth can also increase as a result of sediment deposition induced by traditional erosion control devices such as contour grass strips.
Lower slopes than on adjacent land are preferentially associated with old, deep-seated, slide-moving, large landslides on pelite rock. Such deep-seated movements are known to lower the local relief (Korup, 2006). The low slopes in these landslides are found down the scarps, in the material displacement zones, especially in their accumulation parts (Cruden and Varnes, 1996). These lower slope areas are known to be favorable for human settlement in mountainous regions (Hewitt, 2010). But also, on these landslides, the risk perception is lower. In contrast, the steeper slopes associated with shallow, recent, flow movement, medium-sized landslides and on the granites (table 3.2) may results from the failure surface leaving a rugged relief in place. These are primarily landslides from the October 2014 event.

The higher stone and sand content (Table 3.2) are primarily found on the recent shallow landslides initiated in October 2014. A substantial amount of regolith and colluvium has been ripped away leaving behind the bedrock. Most of these landslides were triggered in the zone where the substratum is formed by granites. Field observations show that even in the accumulation zones, the dominant materials are stone and sand with a lower proportion of clayey material. These landslides are less favourable for valorization, according to the farmers, because of the excessive permeability of the soil and poorly-developed A-horizon. However, near communication routes or villages, the blocks of stone or the sand present in these landslides constitute a physical or financial resource through their use and/or sale as building materials. The lower stone content in the pelite landslides (Table 3.2) could be explained by the fact that the blocks of stone, uncovered at the time of triggering, were used for construction or placed at the boundaries of the fields. In addition, on this lithology, landslides are, in general, old and the farmers have had to use them for several years. Whereas, on the adjacent flanks, the blocks of stone would be more embedded in the ground and therefore difficult to mobilize; hence their presence in the field, reducing the cultivable land.

3.5.3 *Extent and modes of land use in landslide-affected landscapes*

The results of the spatial analysis revealed significant differences in the proportions of all land uses between the interior of the landslides compared to the adjacent land, except for banana plants (Table 3.4). In particular, though crops are the dominant land use both inside and outside the landslides, the study showed that the proportion of crops are 14% higher within landslides (Table 3.4). This reflects farmers' preference for these sites to provide food for their household throughout the year. This is different, for example, from what has been reported for a region in Poland (Kroh, 2017) as well as in the Flemish Ardennes in Belgium (Van Den Eeckhaut et al., 2009), where landslides deemed at risk, are preferentially devoted to forestry compared to adjacent lands dominated by crops.

Notwithstanding these overall differences in land use between the inside and outside of landslides, the regression analysis revealed that farmers adapt their choices of land uses to the characteristics of the landslides (**Appendix Table B.6**). The higher differences in proportion of crops in the case of recent and flow-type landslides in regard to adjacent lands may reflect the natural limitations of land inside these landslides.

The greater proportions of forest cover inside large slides (Table 3.5) could be explained by the fact that such landslides are often old (**Appendix Table B.3**) and have therefore been valorized for a long time. Indeed, on these landslides, the forest cover is maintained on the most unstable zones (Fig. 3.3). As for the lower proportion of trees within the flow and medium-sized landslides (Table 3.5), this could be the result of the recent destruction of the existing trees during the 2014 rainfall event.

With respect to banana plants, although their proportions are not significantly different inside and outside landslides overall (Table 3.4), the evidence indicates that their proportions are higher within the old landslides compared to the adjacent lands and lower in recent landslides (Table 3.5 and **Appendix Table B.6**). Regarding the higher proportion of banana plants in old landslides, this may result from the existence of natural conditions (wetter soil, shallower slope, deeper soil...) that are favourable for this crop. Indeed, banana plants are rather demanding crops requiring good moisture, smaller slope and deeper soils for optimal production (Gaidashova et al., 2009). On the recent landslides, the natural conditions for growing banana plants are less favourable (drier soil, shallower soil…) and farmers prefer to plant them outside where more favourable conditions are present.

Finally, the overall higher proportion of pasture outside the landslides (Table 3.4) results from the opportunities that are created inside landslides for more lucrative or productive activities. Nevertheless, the contrast is stronger upstream than downstream (Table 3.5 and **Appendix Table B.6**), which may be explained by the current trend to convert some recent, less fertile, landslides to pasture for dairy cows (temperate breeds) that are better adapted to the cooler climates of higher elevations (Hanotte et al., 2000; FAO, 2003). According to the lithology, the difference in proportion is much greater on pelites than on granites. The natural conditions inside landslides on pelites are more favourable (see Table 3.2: lower slope, higher fertility, deeper soil, wetter soil, less stony) for more productive or lucrative activities (e.g., banana plants). Besides, it is on the granites that the landslides triggered in October 2014 are dominant. These recent landslides are less favourable for cultivation.

Besides the fact that landslides are used preferentially for certain activities, the surveys and field observations revealed that farmers also take into account variations in natural conditions within the landslides to manage the land. Indeed, considering the case of an old, deep-seated and large slide (Fig. 3.3), the varying natural conditions within the landslide are the source of a diversity of ecosystems adapted to the landforms (Alexandrowicz and Margielewski, 2010; Temme, 2021). Wilcke et al. (2003) show, for example, that the different ecosystems within a large deep-seated landslide are the basis for differences in soil fertility, soil fertility being better in the accumulation zone than in the escarpment zone. Constructions are, for convenience, located preferentially in the flatter zones near the toe, where, in addition to slope stability, road accessibility is easier. Forestry activities are located preferentially in the scarps where slope, soil depth and soil moisture are less favorable for growing rainfed or perennial crops. The roots of the trees may also play a role in stabilizing shallow instabilities that could impact the escarpments(Milledge et al., 2014; Sidle and Bogaard, 2016). The presence of trees also reduces soil erosion by torrential runoff, avoiding concentration of surface water that could, when infiltrating, generate localized increase of landslide activity (Broothaerts et al., 2012; Dille et al., 2022). Pasture is preferentially located on the dry areas of the escarpments, near the houses and, temporarily, where the land is fallow. Banana plants and food crops are grown preferentially in the deeper and/or wetter, generally more fertile, parts of the landslides. The variability of land use choices not only depends on the variability in natural conditions inside the landslide but may also depend on the land tenure status of the farmer. For example, a sharecropper may not be authorized to plant perennial land uses such as banana plants and eucalyptus because contracts can be of very short duration. In wetlands, the sharecropper will prefer to grow market garden crops.

3.6 Conclusions

Adaptations to landslide-related risks lead populations to transform certain constraints into opportunities. Here, using questionnaires of farmers and a spatial analysis of vegetation conditions, we investigated the logics underlying the land use of landslides. The two analyses were complementary and allowed, to a large extent, their simultaneous validation. This study shows that farmers are familiar with landslides and have some insight into assessing the levels of risk they face over time. Their experience in managing lands within landslides keeps them committed to developing these particular sites. The motivation for valorization depends on the characteristics of the landslides and the natural conditions that prevail there. Old, large deep-seated slides are landslides that farmers value more because of favourable natural conditions such as soil fertility, soil moisture, soil depth, presence of flats, low rock and sand load. On the other hand, recent, shallow landslides, with flow movement are less appreciated for valorization. In particular, crops and banana plants are preferred within the old large deep-seated landslides.

Our study on the way people live on landslides is unique and the logics of the land uses of the unstable slopes we highlighted here have to be seen as region specific. This calls for further investigations elsewhere in the world where cultivation practices and the perception of hazards and risks are different. Better understanding the reasons for the settlement of rural populations on unstable landslides may help devise better risk mitigation strategies.

Chapter 4

The disappearance of a disaster: vegetation cover change following a landslide–flash flood compound event in a human-influenced landscape of DR Congo

While natural disasters capture headlines and national attention short-term, the work of recovery and rebuilding is long-term."

Sylvia Mathews Burwell

4.1 Abstract

Scars associated with natural hazards are commonly not permanent. Their disappearance from the landscape over a few years calls into question any assessment of where and when future disasters might occur. This is obviously true, in particular, in zones where natural hazard occurrences are not well recorded and mapped. This problem of lack of data is exacerbated when, for example, natural regeneration of vegetation after a disturbance is rapid. The present study aims, therefore, to quantify the rate of vegetation cover change in source and transport-deposit zone scars after a landslide - flash flood compound event that occurred in 2014 in a populated rural region of DR Congo. The study is also interested in understanding the role of environmental factors that are related to the vegetation cover change. Combining satellite-derived NDVI time series and accurate field observations, we show that positive trends in vegetation cover change are observed in all the impacted zones. However, we show that this vegetation regrowth was faster in the transport-deposit zones than in the source zones due to lower slope gradients (favourable for soil moisture) and human activities (cultivation, mining of the debris). In the source zones the vegetation growth is overall slowed down because of (de)stabilization processes that followed the initiation of landslides and soil erosion that prevails on these steep slopes. Our study demonstrates the complexity of the local natural and human-related processes that are associated with the vegetation cover changes after the occurrence of natural hazards. Understanding site-specific contexts of the human-nature nexus is key to lay out efficient disaster risk reduction strategies.

Keywords: Visibility of natural hazards, vegetation cover change, geomorphological compound event, human-nature nexus, DR Congo

4.2 Introduction

Every landscape is shaped by histories of natural hazards and associated disasters (Wisner et al., 2014; Sidle et al., 2017; Leroy, 2022). However, the visual scars associated with natural hazards are commonly not permanent, even for the most impactful ones (Beguería 2006; Migoń and Pijet-Migoń, 2019). The disappearance of the landscape disturbances left by disasters challenges any assessment to predict where and when future dangers can occur (Palang et al., 2005; Antrop, 2005). It is specifically true in regions where natural hazard occurrences are not well recorded and mapped (Asare-Kyei et al., 2017). This problem of lack of data is exacerbated where, for example, the natural regeneration of the vegetation after a disturbance is rapid and the reclamation of the land is important (Beguería 2006; Stark and Passalacqua, 2014; Löf et al., 2019). Furthermore, the scars, if poorly covered by vegetation, may constitute a source of sediment during subsequent rainstorms. It is therefore important to understand how the natural or human-induced vegetation cover inside hazard-related scars evolves in time, in particular when disaster risk reduction (DRR) strategies must be laid out (Nakileza et al., 2017; Pandey et al., 2022; UNCCD, 2022).

Rainfall-triggered landslides associated with intense convective rainfall can occur in clusters, sometimes featuring several hundreds of slope failures accross a rather limited area (Hungr et al., 2014; Clark et al., 2016). These landslides are commonly rapidly-moving slope processes displaying flow behaviour and high mobility (Cruden and Varnes 1996; Hungr et al. 2014). Such movements strongly disturb the vegetation and their visual signature in a landscape is substantial (Beguería, 2006). In addition, these landslides can connect easily to the thalweg and river network, feeding sediment into debris flows and debris-rich flash floods (Borga et al. 2014; Hungr et al. 2014). The compound and cascading nature of these rainfall-triggered processes associating landslides with flash floods (Tilloy et al., 2019; Zscheischler et al. 2020), here after called

LFF compound events, will exacerbate the impacts on the landscape and therefore their signature.

The evolution of the vegetation after the occurrence of these LFF compound events and the factors driving this disappearance have remained hitherto overlooked. Firstly, the natural vegetation cover change is expected to depend on the local climatic conditions (Hu et al., 2018; Cheng et al., 2022). Secondly, the local lithological, topographic, and soil/regolith conditions of the disturbed landscape could also play a role in the spatio-temporal vegetation cover change patterns (Shiels and Walker 2003; Shiels et al. 2008; Yang et al. 2018; Yunus et al. 2020; Saito et al. 2022). Lastly, in inhabited regions, the vegetation regrowth can be altered by human intervention, i.e., through tree planting but also agricultural activities (Pandey et al., 2022; Chapter 3 of this thesis)

Tropical mountainous regions where convective rainfall are known for being particularly intense and frequent are hotspots of LFF compound events (Temple and Rapp 1972; Jacobs et al. 2016; Fowler et al. 2021; Dewitte et al. 2022). These less-researched environments (Gariano and Guzzetti 2016; Maes et al. 2017; IPCC 2021) are also places where high population densities are common, and on the rise, leading to increased exposure to disasters (Seto et al. 2012; Tellman et al. 2021; Raju et al. 2022). Until recently, documenting with accuracy the vegetation cover change of LFF compound event impacted zones in these mountainous regions would have been challenging. Nowadays however, when combined to field observations, Earth observation data such as the open access Sentinel-2 data offer a good trade-off between pixel resolution, revisit time, and duration of the data acquisition period, even in cloud-covered tropical environments (Cheng et al. 2020; Lissak et al. 2020; Scheip and Wegmann 2021).

The goal of this research is therefore to document the vegetation cover change of a LFF compound event in an inhabited tropical mountainous region using a combination of satellite remote sensing and field observations. More specifically, (1) we quantify, over a few years, the vegetation cover change in the different zones affected by a major rainfall event and (2) we analyze the environmental factors presumed to have links with this revegetation. We focus on the western branch of the East African Rift, a landslide and flash flood hotspot at the continental level where population is particularly vulnerable (Jacobs et al. 2016; Monsieurs et al. 2018; Depicker et al. 2021b). Through a site-specific analysis, we want to bring insight into the complexities of the natural-human nexus around natural hazard disasters.

4.3 The Kalehe October 2014 landslide and flash flood event: natural and anthropogenic context

On the 25th of October 2014, an intense convective rainfall event triggered landslides and flash floods in the region of Kalehe (South Kivu, DR Congo), sweeping away houses, cropland, pastures and trees, causing more than 100 fatalities ("7sur7", 2014; Radio Okapi, 2014; OCHA, 2015). Using a Pléiades image (2 m resolution for multispectral bands) of December 2014 available also in Google Earth (See Section 4.3.1, Fig. 4.3) we identified 634 shallow landslides (depth of the surface of rupture of maximum a few meters), the very large majority of them being debris avalanches and debris slides. Of these landslides, 346 were directly connected to the thalwegs and provided material to 17 debris flows - debris-rich flash floods that reached Lake Kivu (Maki Mateso et al., 2023).

The hillslopes of the study area are of fairly similar age, all associated with the formation of the rift and the rejuvenation of the landscape (Depicker et al., 2021a). However, they are composed of two different groups of lithologies (Fig. 4.1a). Detailed information on specific characteristics and properties of the regolith and colluvium material does not exist in the region. Nevertheless, the regolith profile generally appears less deep and sandier on the areas where granites dominate (personal field observations; Fig. 4.7a,b, d-f).

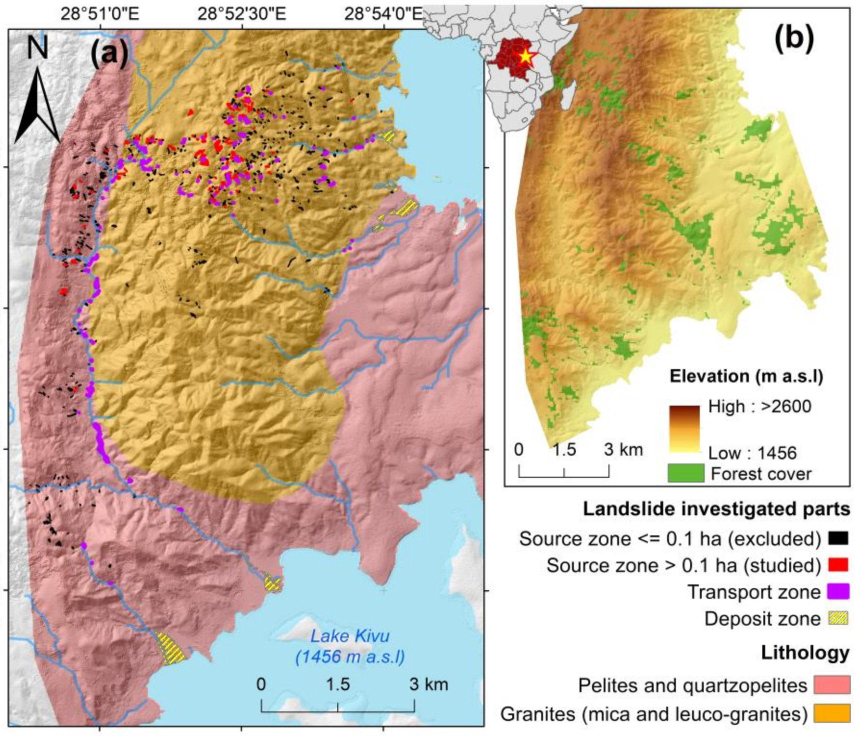


Figure 4. 1: *(a) Landslides and flash floods triggered on October 25, 2014 by an intense convective rainfall. The relief and hillshade are derived from a 5-m resolution TanDEM-X digital surface elevation model (Albino et al. 2015; Dewitte et al. 2021). The lithology is from Laghmouch et al. (2018). (b) Elevation of the study area and the remaining forest cover in 2016 (ESA, 2016).*

The Kalehe region is located in a savannah/monsoon climate zone (Peel et al., 2007) where elevation tempers the temperature and relief creates orographic rainfall. The two wettest months are September and May and the dry season spans the June-August period. The natural vegetation is mostly montane forest; which was still present over the largest portion of the study area in the 1950's (Maki Mateso et al., 2023). Deforestation has occurred since then, mostly during the 1950-2000 period (Basnet and Vodacek, 2015; Depicker et al., 2021b). Deforestation is mainly driven by the demand for agricultural land (Depicker et al., 2021b), in response to a rapid increase in the population density in this region of DR Congo, from 17 to over 200 inhabitants/km² between 1958 and 2015 (European Commission and Joint Research Centre (JRC), 2015).

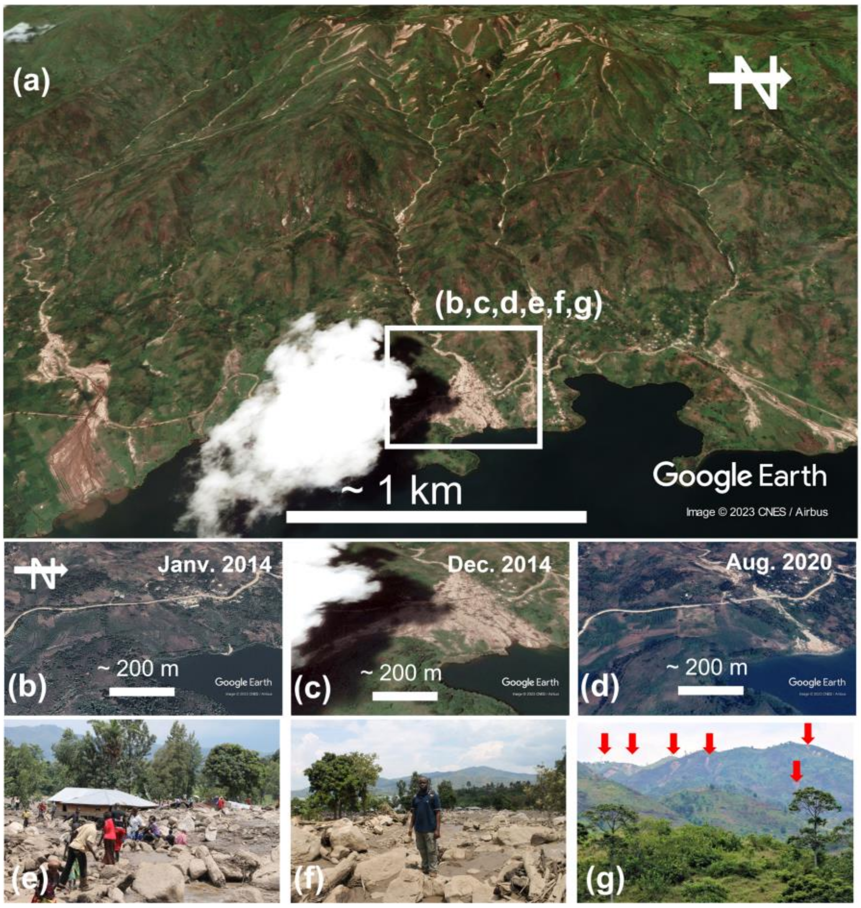


Figure 4. 2: *Landslides and flash floods triggered by the intense convective rainfall of October 25, 2014 in the Kalehe region (-2.047° S, 28.889° E). (a) Large portion of the compound event (image from December 2014). (b) Situation in January 2014 before the disaster, with a focus on the Rambira village where hundreds of fatalities and missing people were reported, and many houses destroyed. (c) Situation in December 2014, a few weeks after the disaster. (d) Situation in August 2020, where a deep-seated landslide triggered about six years after the October 2014 event, provided debris to the river. (e, f,g) Photos taken in Rambira village 48 hours after the 2014 disaster. (g) Shallow landslides triggered during the 2014 event (red arrows indicate source areas). Images (a,b,c,d) are from © Google Earth.*

4.4 Materials and methods

4.4.1 *Sources of information*

The first field visit took place two days after the disaster on 27 October 2014. Since then, field visits have been carried out twice a year. These observations together with interviews with local stakeholders and farmers (Maki Mateso et al., 2022) allowed to capture subtleties in vegetation cover change that cannot be detected from remote sensing alone.

For the temporal analysis of the vegetation cover change (see Section 3.2.1), we primarily used Sentinel-2 images (July 2015 – April 2021). Sentinel-2 images offer a good trade-off between the spatial resolution of 10 m, the period of analysis since June 2015 and the 10-day acquisition frequency (Wang and Atkinson 2018). However, for our study area, the first available Sentinel-2 image is from April 2015 (Figure 4.3), shortly after the start of the Sentinel-2 mission. Hence a November 2014 Pléiades image was used to characterize the situation soon after the occurrence of the event.

The NDVI-analysis for the Pléiades image was performed on ArcMap 10.6.1. For Sentinel-2, the analysis and extraction of NDVI images (see Section 4.2.1) was performed by means of a Python script using the Google Earth Engine code editor (https://code.earthengine .google.com/). The analysis was performed on a total of 26 Sentinel-2 images that had < 20% cloud cover over the study area (Fig. 4.3). When several images were available over a period of a few weeks, mainly during the dry seasons, we selected the image that had the best visual quality since a higher temporal resolution at a specific time of the year would not allow to better grasp the vegetation dynamics trends over several years. We also used © Google Earth images for validation and qualitative analysis (Fig. 4.3). The first image available is from December 06, 2014, just a few weeks after the disaster, and was used as a reference image for the inventory (see Section 4.2).

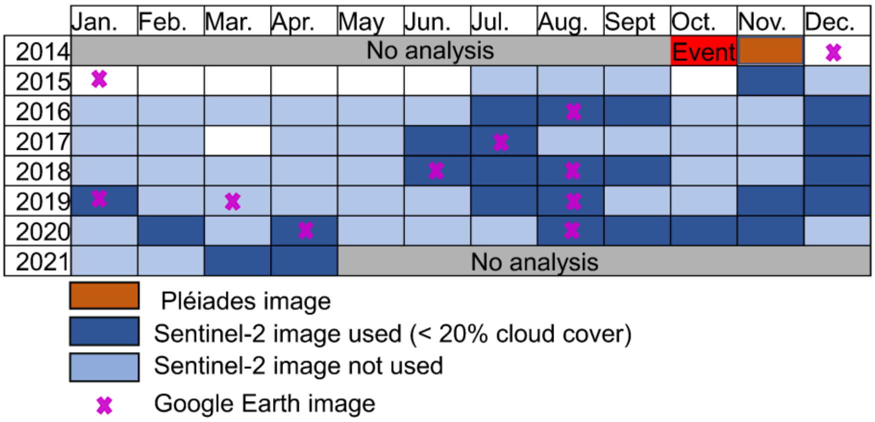


***Figure 4.3**: Availability and use of satellite images after the occurrence of the October 2014 event. For Sentinel-2, only images with < 20 % cloud cover are included in the 2015-2021 NDVI time series analysis. Google Earth imagery is used for manual mapping and validation.*

For the analysis of vegetation cover change in impacted zones, we manually differentiated the source zones of the shallow landslides from the transport zones and deposit zones of the debris flows and flash floods (Fig. 4.4). To avoid the likely impact of mixels caused by the spatial resolution of the Sentinel-2 images, we removed from the impacted zones an interior buffer of 10 m. Within the transport and deposit zones, we removed the talweg/river areas (plus a 10-m buffer outside their limits) that cross them in order to minimize the inclusion of pixels related to the reflectance of water. Next, after these two operations, we discarded all the zones smaller than 10 pixels (i.e. < 0.1 ha) in order to study a sufficiently high number of pixels per zone due to the spatial resolution of Sentinel-2 images. These selection criteria allowed retaining a total of 145 individual impacted zones: 92 landslide source zones, 40 transport zones, and 13 deposit zones.

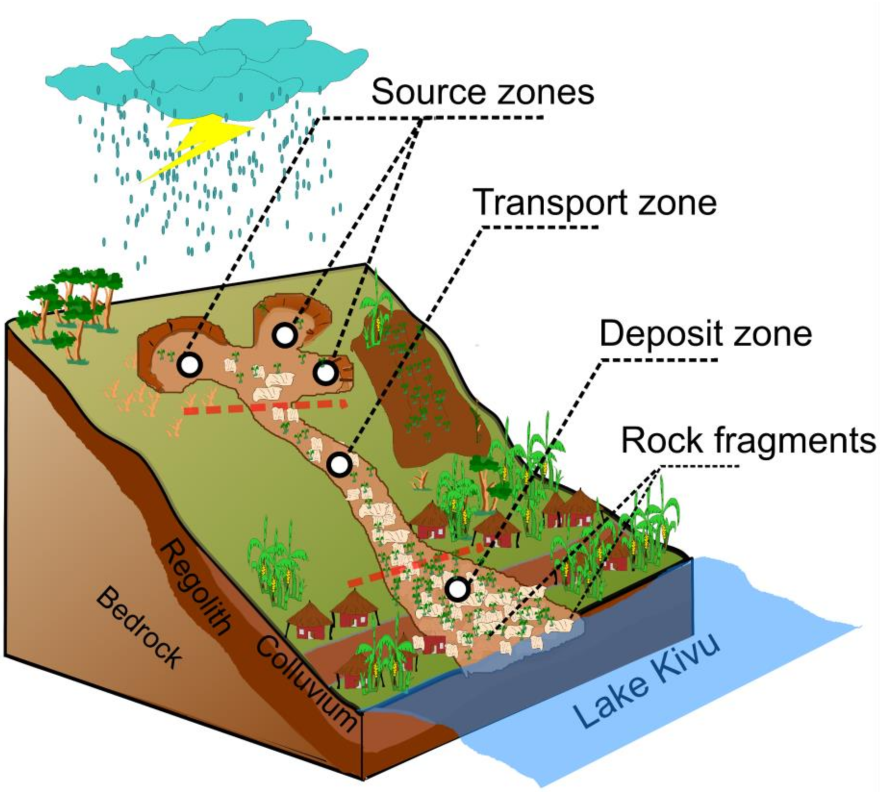


Figure 4.4: *Differentiation of the landslide – flash flood compound event in three types of impacted zones where different processes and therefore vegetation disturbance take place. The source zone is where the shallow landslides take place. The transport zone is where the debris flows dominate. The deposit zone is where flash floods dominate.*

For the needs of the NDVI analysis (see Section 4.3.2.1), we delimited non-impacted 'control' areas between 50 and 200 m around each of the 145 impacted zones. Because impacted zones were sometimes close to each other, care was taken to exclude impacted zones from these 'control' areas. The 50-m buffer was chosen to avoid mixels and zones that were affected by subsequent reactivations. The 200-m outer limit was chosen in order to have a sufficiently large 'control' area yet not too large in order to ensure sufficient similarity with the impacted zones in terms of aspect, lithology, etc..

To assess the spatial factors that govern vegetation cover change (see Section 4.3.2.2), we relied on a series of predictors. The topographic predictors (Figure 4.1, Appendix **Figure C.1**) were extracted from the 1 arc second SRTM DEM (https://lpdaac.usgs.gov /products/ srtmgl1v003/): elevation, slope angle, slope aspect, profile curvature, plan curvature, topographic wetness index (TWI). The topographic predictors are all continuous except for slope aspect, which is categorized in eight dummies, the east direction being chosen as a reference to consider the dominant trade wind regime of the region. Lithology (pelites as reference) (Laghmouch et al., 2018) and forest cover ('no forest' as reference) (ESA, 2016) are the other two categorical predictors considered in the analysis (Fig. 4.1).

Monthly rainfall values were extracted from the satellite product Integrated Multi-satellitE Retrievals for GPM (IMERG_V06) (Huffman et al., 2019) using Google Earth Engine. Nakulopa et al. (2022) showed that these data can be used with confidence in a study carried out in the neighboring region of the Rwenzori Mountains where the main environmental characteristics are similar. The spatial resolution of the IMERG data is 11 km. Given this low spatial resolution, we are not using IMERG for a spatial characterization of rainfall distribution.

4.4.2 Data analysis

We used an approach based on relative NDVI values (NDVI of impacted zone relative to the corresponding non-impacted zone; see further) to analyze the trends and spatial patterns in vegetation cover change over the different impacted zones. Using relative values facilitates comparisons between different images over time (Peters et al., 2002; Nagai et al., 2010), which is specifically needed in our case since the available images were not acquired at the same period of the year (Fig. 4.3).

4.4.2.1 *The time component: overall trends in vegetation cover change*

For the overall trend assessment, we calculated seven relative NDVI values for each of the 27 satellite images taken individually (1 Pléiades and 26 Sentinel 2). The seven NDVI values are extracted for different types of processes as follow: (1) all source zones pooled together, (2) all transport zones pooled together, (3) all deposit zones pooled together, and (4) all transport and deposit zones pooled together (noted as transport-deposit zones). In addition, source zones were discriminated by three size (5,6,7) categories: 1000-2000 m², 2000-300 m² and > 3000 m² in order to investigate whether vegetation recovery was affected by the size of the source zone.

For example, for all the 92 source zones pooled together, we calculated an average NDVI value for each zone separately and then an average was calculated over all the pixels. Then, similarly, we calculated an average NDVI value for all the pixels in the respective non-impacted zones, i.e. the 'control' areas around all the 92 source zones. The corresponding ratio between these two average values gives a relative NDVI value (Eq. 1). When the relative NDVI is greater than 1, it indicates that the NDVI values are higher in the impacted zone than in its direct non-impacted surroundings.

$$NDVI\ relative = \frac{average\ NDVI_{impacted\ zone\ type}}{average\ NDVI_{non-impacted\ zone\ type}} \qquad (1)$$

We fitted an adapted saturation growth function (Eq. 2) to compare the seven relative NDVI time series, each made of 27 temporal observations. The adapted saturation growth function is applied to our observations to predict the growth of the vegetation characterized by rapid initial recovery and progressive slowing down until stabilization (Damgaard et al., 2002; Sharkey et al., 2016; Xu et al., 2018). A sigmoïd function might also have been used but insufficient data during the first year of recovery did not allow identifying the occurrence of an initial latency.

$$Y = a + (1 - a) * \left(\frac{T}{(b+T)}\right) \qquad (2)$$

Where Y is the relative NDVI at time **T**, **a** (Y-intercept) corresponds to the initial relative NDVI value immediately after the occurrence of the compound event, and **b** is a growth/decay factor.

In a first step, using Eq.2, Student's t-test allowed a pairwise comparison of the vegetation growth rate (growth/decay factor b) between the different zones studied. In the first step, the zones compared were the source, transport, deposit, and transport-deposit zones. Secondly, the source zones were compared according to their size categories, i.e. all the source zones (n=92), the classes of 1000-2000 m² (n=32), 2000-3000 m² (n=29) and the one above 3000 m² (n=31).

Secondly, the time series analysis was also applied separately on the 145 impacted zones taken individually. For each of the 145 time series, we fitted an adapted saturation growth function (Eq. 2) that allowed to derive for each individual impacted zone a Y-intercept value (initial value) and b growth coefficient (Eq. 2). Besides the analyses of these two coefficients, we evaluated the initial "acceleration phase" of vegetation cover change by calculating the difference between the first relative NDVI value of the Sentinel-2 image and that of the Pleiades image. After checking the conditions of normality of data distribution for the Y-intercepts, the first acceleration phase and growth coefficients, we performed an analysis of independent-samples T test to compare means of these two groups (Ross and Willson, 2017).

4.4.2.2 *The spatial component: vegetation cover change patterns and predictor variables*

Linear regression models (Weisberg, 2005) were used to determine, for each group, the relationships between the dependent variable (either Y-Intercept, growth coefficients and first acceleration phase: see the last paragraph below in section 4.4.2.1) and the topographic, lithological and forest cover predictors assumed to influence the vegetation cover change patterns. We included predictors in the models based on the overall resulting R^2, the significance of the ANOVA test through Fisher's analysis (F) for model performance; the significances of the explanatory variable being taken individually. The predictors were also tested for multicollinearity (VIF > 2; Van Den Eeckhaut et al., 2006); meaning that the predictor with a VIF > 2 has a linear relationship with one or more other predictors (Alin, 2010). Statistical analyses were performed with IBM SPSS Statistics (Version 26).

4.5 Results

4.5.1 Overall vegetation cover change trends

A visual comparison of the growth curves of the different study zones (Fig. 4.5a) shows that the cover change is more important in the transport-deposit zones than in the source zones. In the source zones (Fig. 4.5b), the vegetation cover change appears to be similar for the different sizes of the source zones. A pairwise comparison (T-test) of vegetation growth rates (Table 4-1) shows that: (1) there is no significant difference between the transport and deposit zones in terms of vegetation recovery rate ($p > 0,05$); (2) vegetation in source zones are recovering more slowly than in transport-deposit zones combined. Analysis of the initial growth rate and growth factor provide consistent results (Table 4-2); (3) within source zones, there is no difference in the rate of vegetation recovery according to their size classes ($p < 0.05$).

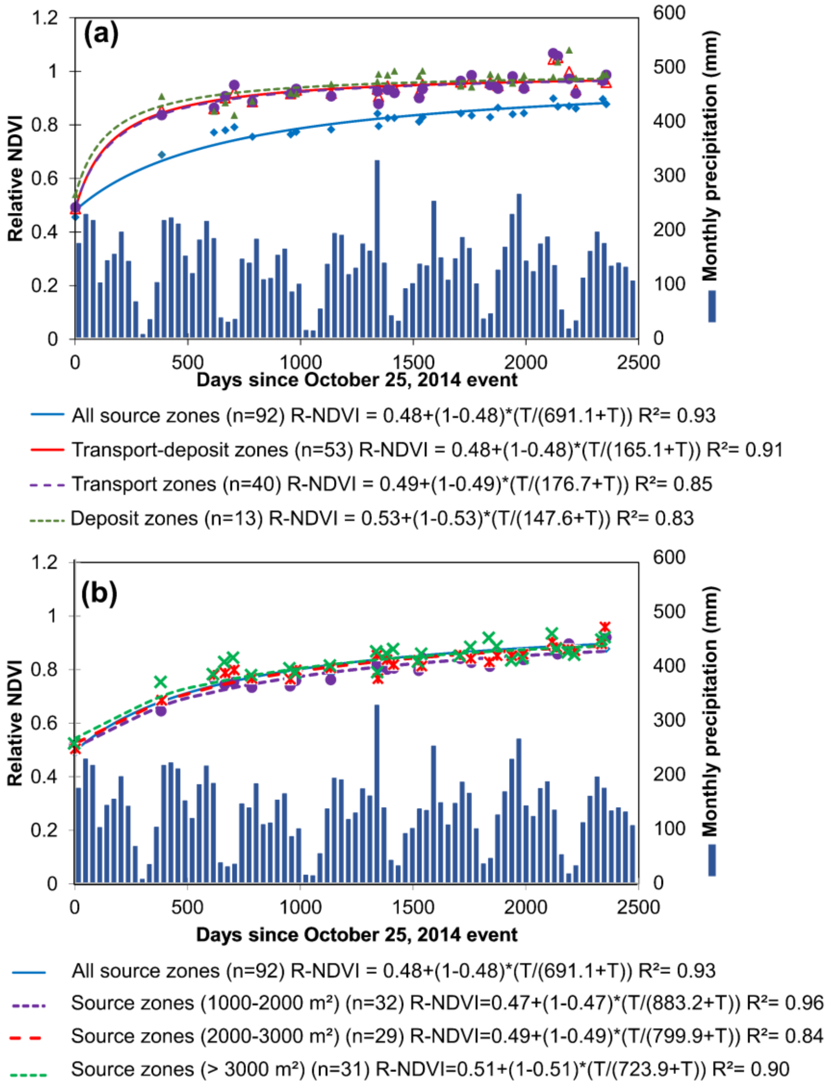


Figure 4.5: *Change in relative NDVI for the impacted zones. NDVI values are expressed relative to the control zones outside the impacted zones. a) Evolution of the relative NDVI for the source, transport and -deposit zones. b) Evolution of the relative NDVI for the source zones as a function of the size categories. Red dots mark the date of the Sentinel-2 images used for the analysis. Day 0 corresponds to the date of occurrence of the compound landslide-flash flood event.*

Table 4- 1: Pairwise comparison on growth/decay rate of vegetation cover change

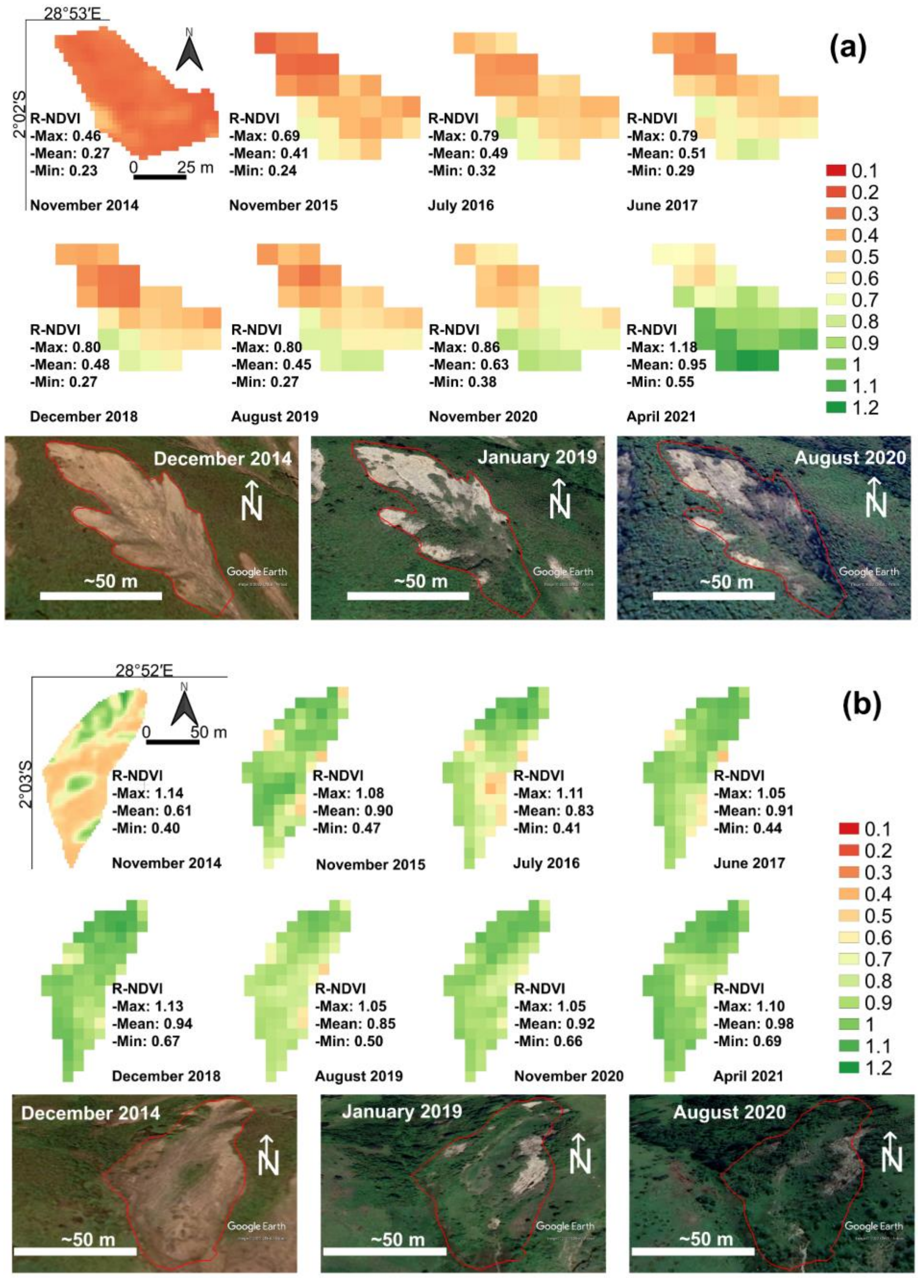
	Estimate difference in growth/decay	t-test	p-value
All sources vs Transport deposit	-563.07	-9.52	< 0.001
All sources vs Transport zones	-553.32	-9.372	< 0.001
All sources vs Deposit zones	-598.71	-10.05	< 0.001
Transport deposit vs Tranport zones	9.74	0.17	0.87
Transport deposit vs Deposit zones	-35.65	-0.6	0.55
Tranposrt zones vs Deposit zones	-45.39	-0.77	0.44
All sources vs Sources zones (1000-2000m²) (n=32)	-18.99	-0.35	0.73
All sources vs Sources zones (2000-3000m²) (n=29)	-40.15	-0.75	0.46
All sources vs Sources zones (>3000m²) (n=31)	-100.75	-1.92	0.06
Sources zones (1000-2000m²) (n=32) vs Sources zones (2000-3000m²) (n=29)	-21.16	-0.39	0.69
Sources zones (1000-2000m²) (n=32) vs Sources zones (>3000m²) (n=31)	-81.76	-1.55	0.12
Sources zones (2000-3000m²) (n=29) vs Sources zones (>3000m²) (n=31)	-60.6	-1.15	0.25

Overall, the vegetation cover change trends show, between all source zones (n=92) and all transport-deposit zones (n=53), that (1) at the initial point (Y-intercept) at the date of the event, the different zones have a similar vegetation cover (Fig. 4.5a,b; Table 4-2). But, (2) the growth factor of vegetation cover change and the first acceleration phase are different between these zones.

Table 4-2: Mean difference between source zones and transport-deposit zones for Y-intercept, difference Y-intercept and first acceleration phase, and growth/decay factor.

			Source zones	Transport and deposit zones
		N	92	53
Parametric tests	Y-intercept	Mean	0.49	0.51
		Std. deviation	0.09	0.15
		F	0.33	
		p-value	no difference	
	First acceleration phase	Mean	0.18	0.34
		Std. deviation	0.16	0.24
		F	23.843	
		p-value	***	
Nonparametric tests	Growth/decay factor	Mean rank	84.32	53.36
		Wilcoxon	2828	
		Z	-4.27	
		p-value	***	

In November 2014, a relatively similar vegetation cover deficiency can been seen in the impacted zones (Figure 4.6). One year later, the vegetation cover change rate is highly variable from one source zone to another. In the example of Figure 4.6a, vegetation cover change is mostly concentrated at the toe of the landslide where the displaced material was deposited. The rate of vegetation growth is lower on the steepest parts. The example of Figure 4.6b shows a landslide where the vegetation cover change is much faster. In less than one year (Dec. 2014 – Nov. 2015) most of the failed slopes were vegetated. The situation in Figure 4.6c is an example where the vegetation cover change is partly halted due to the valorization of the source zone for agricultural purposes.


(a)
28°53′E
2°02′S
N
0
25 m
R-NDVI
-Max: 0.46
-Mean: 0.27
-Min: 0.23
November 2014
R-NDVI
-Max: 0.69
-Mean: 0.41
-Min: 0.24
November 2015
R-NDVI
-Max: 0.79
-Mean: 0.49
-Min: 0.32
July 2016
R-NDVI
-Max: 0.79
-Mean: 0.51
-Min: 0.29
June 2017
R-NDVI
-Max: 0.80
-Mean: 0.48
-Min: 0.27
December 2018
R-NDVI
-Max: 0.80
-Mean: 0.45
-Min: 0.27
August 2019
R-NDVI
-Max: 0.86
-Mean: 0.63
-Min: 0.38
November 2020
R-NDVI
-Max: 1.18
-Mean: 0.95
-Min: 0.55
April 2021
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
December 2014
January 2019
August 2020
~50 m
Google Earth
(b)
28°52′E
2°03′S
N
0
50 m
R-NDVI
-Max: 1.14
-Mean: 0.61
-Min: 0.40
November 2014
R-NDVI
-Max: 1.08
-Mean: 0.90
-Min: 0.47
November 2015
R-NDVI
-Max: 1.11
-Mean: 0.83
-Min: 0.41
July 2016
R-NDVI
-Max: 1.05
-Mean: 0.91
-Min: 0.44
June 2017
R-NDVI
-Max: 1.13
-Mean: 0.94
-Min: 0.67
December 2018
R-NDVI
-Max: 1.05
-Mean: 0.85
-Min: 0.50
August 2019
R-NDVI
-Max: 1.05
-Mean: 0.92
-Min: 0.66
November 2020
R-NDVI
-Max: 1.10
-Mean: 0.98
-Min: 0.69
April 2021
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
December 2014
January 2019
August 2020
~50 m
Google Earth

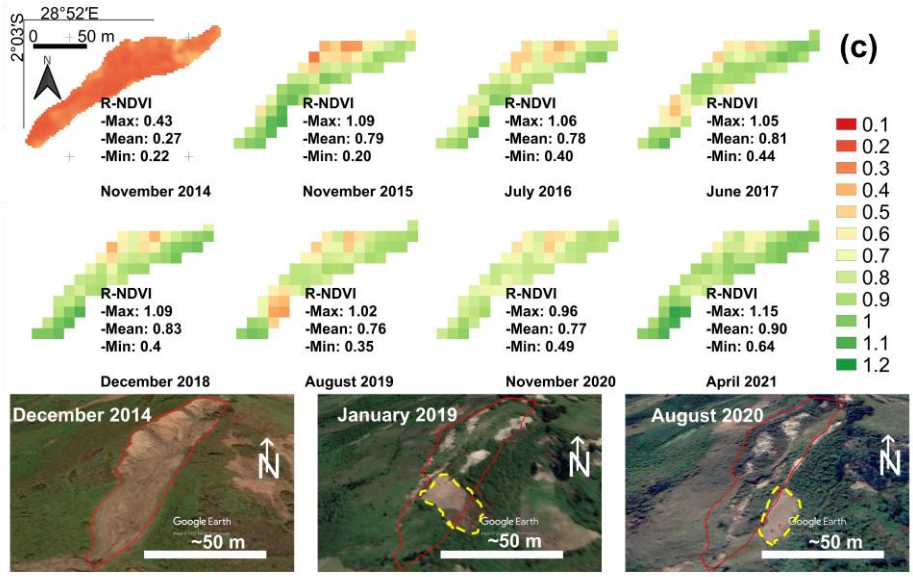


Figure 4.6: *Examples of relative NDVI value changes for different source zone contexts. (a) Landside with pervasive ground deformations and signs of high activity, (b) Landslides with natural vegetation cover growth. (c) Landslide with land reclamation for use as cropland (zone delineated in yellow). The relative NDVI scale ranges between 0.1 and 1.2; values above 1 indicate that the NDVI values are higher in the impacted zone than in its direct surroundings.*

Field observations provided further insights regarding the role of anthropogenic activities on the vegetation cover change. The latter can be positively impacted through reforestation actions (Fig. 4.7a,b) such as those initiated by non-governmental organizations and local leaders (Head, 2015; OCHA, 2015). In 2015, community nurseries of eucalyptus and grevillea (Fig. 4.7c) were set up and reforestation was done on a voluntary basis for and by farmers who agreed to plant the proposed tree species. During the field campaigns, we noted that eucalyptus trees were better adapted to the transport-deposit zones (gentler slopes, deeper and wetter soils) than to the source zones (steeper slopes, shallower and drier soils). Anthropogenic activities can also have a negative impact on vegetation cover change (Fig. 4.7d,e: slash-and-burn farming and stone or sand extraction). Finally, some land uses, for subsistence crops, are observed within some shallow landslides (Fig. 4.7c and **Appendix Figure C.3**). However, the crops seem to be less adapted especially on the source zones (Appendix Fig. C4.3d-f).

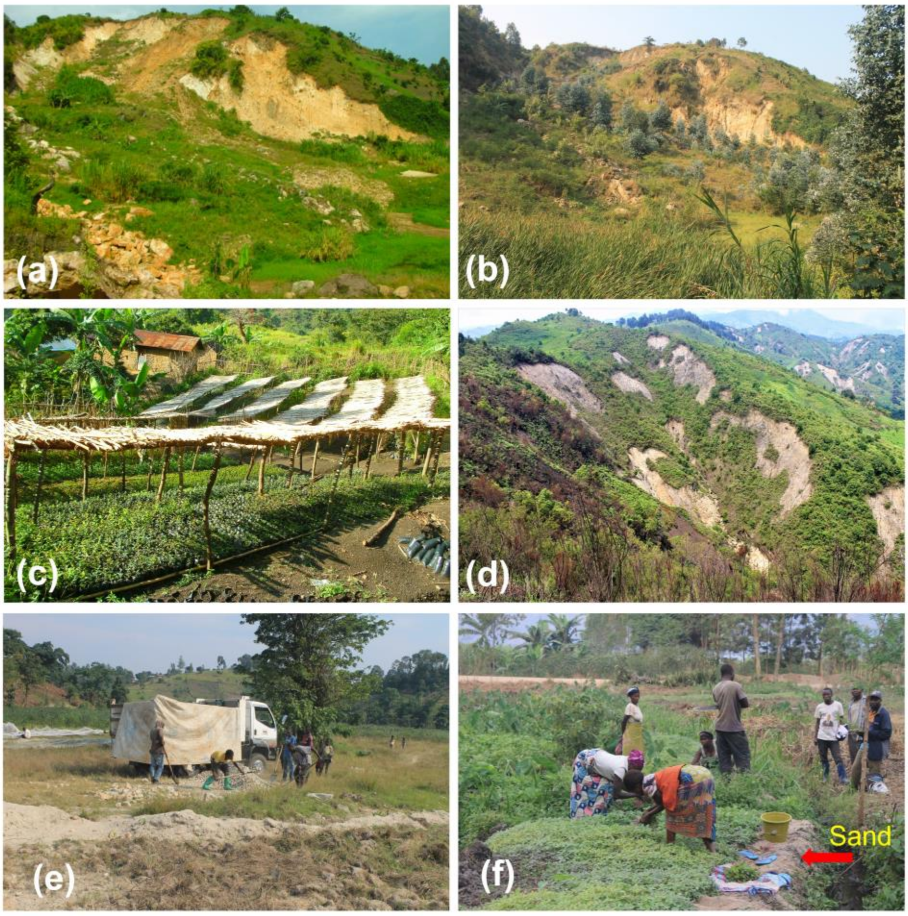


Figure 4.7: *Examples of landslides and land use contexts. (**a**) Reforestation with eucalyptus in December 2016; (**b**) Situation on the same site in January 2021; (**c**) Nursery of eucalyptus and grevillea (2015); (**d**) Disruption of natural vegetation cover change by slash-and-burn (foreground) to reclaim land for agriculture (2021); (**e**) Exploitation of the debris flow – flash flood (2021) deposits as construction material, photo taken in the same area as Figure 4.2f; (**f**) Vegetable crops in the zone through which the flash flood passed; we can see that the soil is sandy (2021).*

4.5.2 Spatial factors controlling vegetation cover change

In the source zones, immediately after the event, the vegetation cover (Y-intercept) is slightly higher on the topographies with lower slopes, favorable for the presence of moisture (TWI), on slope aspects close to the west and in the presence of forest cover (Table 4.3). Whereas, vegetation cover is slightly lower for source zones located on steep slopes and on the granites. As far as growth factors are concerned the vegetation cover change is stabilized in source zones with forest cover and high moisture (TWI) on lower slopes. The initial vegetation cover change during the first acceleration phase is slightly favoured by the concentration of moisture, lower slopes and the presence of forest cover.

In the transport-deposit zones, on steeper slopes, the vegetation cover immediately after the event (Y-intercept) is also higher in lower slopes, favoured by concave topographies (Table 4.3), with a preference for southwest slopes. The growth rates are the highest in the granites; in concave environments; i.e. in conditions that are not favorable during the first acceleration phase.

Table 4-3: *Results of the multiple linear regression models of the Y-Intercepts or growth coefficients or first acceleration (dependent variables) as a function of various predictors for the source zones or the transport-deposit zones. (p-value: * < 0.05, ** < 0.01, ***< 0.001).*

		Source zone (n=92)			Transport and deposit zones (n=53)		
	Dependent variable	Y-intercept	Growth coeff	First acceleration phase	Y-intercept	Growth coeff	First acceleration phase
Model summary	ANOVA (F)	4.259***	5.098***	2.81**	2.472*	2.27*	2.27*
	R Square	0.35*	0.39*	0.26*	34.1*	0.29*	0.29*
	Model coefficients (β)						
	Constant	0.604***	797.702*	0.11	0.714***	284.914	0.371**
Predictors	Granites	-0.089**	269.13	-0.07	0.032	426.04*	-0.216*
	Slope angle	-0.002*	-4.434	-0.005*	-0.010**	-16.351	0.008
	Profile curvature	0.005	-60.213	-0.012	0.080**	228.362*	-0.021
	Slope aspect						
	north	0.020	644.981*	-0.15	-0.12	-413.163*	0.098
	northeast	-0.015	188.272	-0.05	-0.02	-21.752	-0.104
	east	Reference					
	southeast	0.001	83.089	-0.056	-0.02	68.671	-0.081
	south	++++	++++	++++	++++	++++	++++
	southwest	0.051*	20.364	-0.010	-0.245***	-129.645	0.166
	west	++++	++++	++++	++++	++++	++++
	northwest	0.107**	-54.976	0.006	-0.049	261.906	-0.25*
	Forest cover	0.051**	-546.628***	0.075*	-0.121	No	No
	TWI	0.011*	-60.649*	0.019*	++++	++++	++++

Reference modalities for predictors are: lithology = pelites; forest cover = no forest; slope aspect: dummy variables. $^{+++}$: variables with collinearity problem (VIF > 2).

4.6 Discussion

4.6.1 Trends and patterns of vegetation cover change

Although vegetation re-growth was observed on average in all impacted zones during the study period, the differences in vegetation cover change trends for the different impacted zones can be explained by the interaction between geomorphic and anthropogenic factors. The Pléiades image taken just after the event (Fig. 4.2: November 2014) shows that the vegetation signatures of all the impacted zones were similar at that time. The fact that in 2015 the relative NDVI (following the first acceleration phase) values for the transport-deposit zones are much higher than the ones of the source zones (Fig. 4.5a) indicates that vegetation cover change in the lowlands and the flat terrains has been much faster during the 13 months after the occurrence of the compound events (Fig. C2). One reason is clearly associated with the fact that the deposits of the debris flows and flash floods are easily getting stabilized on a flat terrain whereas, as shown on Figure 4.6, landslides in the source zones are prone to lasting processes of (de)stabilization which can be rhythmed by various phases of activity and quiescence. Such processes, that do not seem to be influenced by the size of the source zones (Fig. 4.6a), have not only been observed in the Kivu region (Dille et al., 2019) but also in various other environments, notably through the analysis of vegetation cover change (Dalling and Tanner, 1995; Saito et al., 2022). In addition to this geomorphic context, the reclamation of the land for anthropic activities (agriculture, forestry, …) may also partly explain the faster vegetation cover change during the first 13 months. Indeed, the zones impacted by the debris flows and flash floods were initially the most inhabited ones, crossed by the main roads. Although interviews confirmed that many of the harmed people abandoned the impacted areas, others quickly took advantage of the empty land. Population growth is high in the region (European Commission and Joint Research Centre (JRC), 2015) and flat areas along the lake and accessible by roads are not common. In addition, it must be noted that the debris deposits are source of sand and stones construction material (Fig. 4.7e) (Maki Mateso et al., 2022). The removal of the deposits exacerbates the disappearance of the scars left by the impacted zones and, somehow, allows to return to soil conditions that are more favourable to vegetation growth.

Overall, the sources zones were still not entirely vegetated in 2021. Surely, the natural dynamics of the landslides are to be invoked here. In addition, the source areas are located in steeper contexts where one can easily assume (as shown in Figures 4.7a, b,d) that the fertile layer of the soil has been depleted, hence bringing conditions that are less favourable for spontaneous regrowth, agriculture and land reclamation (Maki Mateso et al., 2022). In addition, soil erosion is more pronounced on these slopes. With respect to the vegetation situation of the transport-deposit zone, in 2021 most of the scars have disappeared (Fig. 4.5a). For the deposit zones, we even observe NDVI values higher than the surroundings (i.e., relative NDVI > 1). One may assume that these places are where the soils are the most humid in the study area, favoring dense regrowth.

The six linear regression models show significant R^2 values. However, these levels of significance are less pronounced for the transport-deposit models than for the source models, especially for the growth rate of the vegetation cover change. One may argue that this reflects a more pronounced impact of human activities on the vegetation cover change growth that are not reflected in the predictors used in the models. Apart from this anthropogenic context, it is interesting to see that a few of the predictors actually play a significant role, humidity concentration (TWI for sources zones and profile curvature for transport-deposit zones) and regolith characteristics being the main ones. In the source zones, the more rapid vegetation cover change in the forest cover could be explained by the influence of the presence of tree roots, the presence of organic matter from the biomass and moisture related to shading that promote plant growth (Beguería, 2006) and seeds of plants located in the surrounding area (Mi et al., 2019). The negative impact of the slope angle on the vegetation cover change of the source zones could be explained by a combined effect of gravity-driven hillslopes processes, maintaining landslide activity, and increased water erosion potential, slowing down the regrowth (Nadal-Romero et al., 2014). The effect of slope aspect, although sometimes significant, must be considered with care as it strongly depends not only on the main dominant topographic characteristics and the seasonality of the north-south position of the sun, but also on the dominant wind characteristics during the extreme rainfall event. The latter issues that are unknown and may not match those of the background climate conditions associated with the prevalence of the east-to-west trade winds.

The trends show that after a period of seven years, 67% of the source zones and 85% of the transport-deposit areas have recovered to within 85% of the adjacent vegetation cover. Our vegetation growth mean values are within a range similar to what has been observed in other regions, e.g., 85-100% recovered between 5 and 10 years (Yunus et al., 2020; Saito et al., 2022) for example.

4.6.2 Implications for disaster risk reduction strategies

At the local level, the disappearance of the disaster scars is closely associated with the reclamation of the land. Such an interaction with human activities seems somehow to be a post-disaster response that is at odds with respect to what we would expect from a community that has been so severely harmed a few years ago. However, such a statement must be pondered. From our interviews it is clear that many of the impacted people left the areas. Nevertheless, as said earlier, the empty land was rapidly reoccupied. As stated by local stakeholders, these new people are not all in the ignorance of the problem (Chapter 3: Maki Mateso et al., 2022), but direct economic benefits dominate over the possible future harms (Depicker et al., 2021b; Chapter 3: Maki Mateso et al., 2022). Furthermore, the authorities are not armed with the legal frameworks and/or practical means such as awareness raising and economic incentives to stop the process. In such a context, it is difficult to implement DRR strategies (Vanacker et al., 2007; Nakileza et al., 2017; Pandey et al., 2022; UNCCD, 2022).

When discussing with local stakeholders, climate change is commonly invoked to blame disasters such as the one analysed in the present study. However, in this specific case, we do not need to invoke it. Studies show that intense convective rainfall conditions such as those of October 2014 are no exception at the regional level (Monsieurs et al., 2018b) and nearly every year such LFF compound events are reported in this part of the African continent (Deijns et al., 2022). Nevertheless, it is worth mentioning that a similar rainfall in this specific area will not have the same impact in the future. The regolith and colluvium material that was swept away during the 2014 event is 'food' that is not available for consecutive disasters, even in a changing climate context, and the time needed for the hillslopes to redevelop new material that matches pre-event conditions can easily be of several thousands of years (Dykes, 2002; Parker et al., 2016). This discussion about future impact must, however, not ignore the potential increase in vulnerability that will result from the rapidly growing population in these hazard-prone landscapes (Depicker et al., 2021b). At the scale of the western branch of the East African Rift, climate change impacts and the probable increase of extreme rainfall events is also a piece of the puzzle that cannot be ignored (Souverijns et al., 2016; Fowler et al. 2021; IPCC, 2021).

4.7 Conclusions

Tracking the vegetation cover change of the different zones affected by the October 2014 LLF compound event is essential to understand the temporality of the visibility of the scars left by the disaster. The source, transport, and deposit zones all show positive vegetation cover change trends, although the source zones are revegetating at a lower rate than the other two zones. In the source zones the vegetation cover change is slowed down because of steeper slopes favouring pervasive hillslope instability and soil erosion; however, in the case where there is the presence of forest, the vegetation cover change becomes faster. The vegetation cover change in the transport-deposit zones is favoured by lower slopes and concentrated soil moisture conditions. Added to that are human activities associated with land reclamation cultivation, debris deposit exploitation. It appears that in both source and transport-deposit zones, the lithology in place plays similar roles for vegetation cover change.

The rural context of the Kalehe region, with strong anthropic disturbances, is a case study in real conditions linked to global changes issues and the increasing vulnerability of populations in tropical regions. Our study demonstrates the complexity of the local natural and human-related processes that are associated with the vegetation cover changes after the occurrence of natural hazards. Understanding site-specific contexts of the human-nature nexus is key to lay out efficient disaster risk reduction strategies.

Chapter 5

Conclusions générales et perspectives

"We cannot stop natural disasters, but we can arm ourselves with knowledge: so many lives wouldn't have to be lost if there was enough disaster preparedness."

Petra Nemcova

"Nous ne pouvons pas arrêter les catastrophes naturelles, mais nous pouvons nous armer de connaissances : tant de vies n'auraient pas à être perdues si la préparation aux catastrophes était suffisante."

5.1 Introduction

La présente recherche doctorale menée sur les versants du Rift à l'ouest du lac Kivu consistait à évaluer les interactions entre les glissements de terrain, l'utilisation des terres et la gestion du sol dans un environnement rural tropical. Trois questions ont guidé notre recherche doctorale : (1) quel est le rôle des facteurs naturels et anthropiques dans la distribution régionale des glissements de terrain dans un environnement anthropisé; (2) quelles sont les logiques qui sous-tendent l'utilisation des terres dans les glissements de terrain ; (3) quelle est la vitesse de revégétalisation des glissements de terrain superficiels et des zones affectées par les coulées de débris-crues éclairs et comment est-elle influencée par les facteurs environnementaux. Les différentes thématiques abordées durant cette recherche doctorale ont permis de dégager quelques résultats saillants qui constituent notre contribution à la science, notamment dans la compréhension de l'interface entre le glissement de terrain et l'anthropisation en milieu tropical. Nous présentons aussi les limitations, les recommandations, les orientations possibles des futures recherches et les implications locales liées à cette recherche doctorale.

5.2 Principales découvertes

5.2.1 *Characteristics and causes of natural and human-induced landslides in a tropical mountainous region: the Rift flanks west of Lake Kivu (DR Congo)*

Caractéristiques et causes des glissements de terrain naturels et anthropiques dans une région montagneuse tropicale : les versants du Rift à l'ouest du lac Kivu (RD Congo)

L'inventaire s'est appuyé sur l'utilisation de plusieurs sources d'images satellites à haute résolution (© Google Earth, TanDEM-X 5 m) et de photographies aériennes des années 1955-58. Ces dernières ont été une plus-value pour différencier les glissements anciens et récents afin de mieux cerner leurs facteurs d'occurrence. Une des qualités de l'inventaire repose aussi sur les intenses campagnes de terrain pour la validation et la compréhension des conditions d'occurrence de certains glissements de terrain. Sur l'ensemble de l'inventaire, près de 30% des glissements de terrain ont été visités sur approximativement 20% de notre zone d'étude. L'analyse de la complétude des différentes catégories de glissements de terrain, à l'exception des récents glissements de terrain profonds et ceux liés aux mines, ont montré qu'en général, tous nos glissements de terrain inventoriés se retrouvent dans des proportions de tailles similaires avec celles retrouvées dans d'autres parties du monde. Les modèles de susceptibilité pour les anciens glissements de terrain profonds et les glissements superficiels ont permis de confirmer nos hypothèses sur les causes d'occurrence des différentes catégories de glissements de terrain. Les anciens glissements de terrain profonds sont liés aux facteurs naturels tels que les conditions topographiques et à l'activité sismique ; tandis que les glissements de terrain superficiels sont liés aux facteurs anthropiques comme la distance aux routes (prise comme proxy de la présence humaine) et la perte de forêt. L'altitude et la pente influencent, simultanément, l'occurrence de ces deux catégories de glissements de terrain. Les glissements de terrain liés aux mines et aux routes sont moins bien prédits par les modèles de susceptibilité, ce qui suppose que leurs occurrences répondent à des facteurs des environnementaux (exploitation minière, route en terres battues moins entretenues, moins d'aménagements de protection, etc.) différents des conditions naturelles d'occurrence.

5.2.2 *Living on landslides: land use on unstable slopes in a rural environment of the Rift flanks west of Lake Kivu (DR Congo)*

Vivre sur les glissements de terrain : utilisation des terres sur des pentes instables dans un environnement rural sur les versants du Rift à l'ouest du lac Kivu (RD Congo)

Dans ce chapitre, les logiques qui sous-tendent la mise en valeur des glissements de terrain ont été étudiées, à l'échelle locale, dans un environnement rural très anthropisé de la région de Kalehe présentant des fortes densités à différentes catégories des glissements de terrain et des susceptibilités élevées. L'échantillonnage stratifié des 70 glissements de terrain a permis d'analyser, indépendamment, les caractéristiques des glissements de terrain. L'enquête de terrain auprès des 82 exploitants et l'analyse spatiale des affectations du sol au sein des glissements de terrain ont abouti à des résultats largement similaires. Les résultats ont montré que presque tous les glissements de terrain, sauf trois, avaient une ou plusieurs formes de mise en valeur, ce qui illustre bien les contraintes démographiques pour l'accès aux terres agricoles. Près de ¾ des exploitants savaient bien qu'ils exerçaient leurs activités sur un glissement de terrain et évaluaient les risques actuels comme élevés à très élevés sur leurs exploitations. L'étude a montré que l'exploitation des glissements de terrain peut être antérieures ou postérieures à leurs occurrences ; ce qui suppose une certaine acceptation des risques encourus vus les bénéfices que tirent les exploitants dans ces environnements particuliers. Par rapport aux terres adjacentes aux glissements de terrain, les conditions topographiques sur les glissements de terrain de grande taille, à mouvement slide, ancien, profond offrent des conditions favorables de mise en valeur en raisons : (1) de la présence de pente plus faible dans les zones de transport et dépôt, (2) une meilleure fertilité, (3) un sol profond issu du transport du régolithe, (4) une humidité permanente dans les zones concaves du milieu. Sur les substrats de type pelites, en plus de la fertilité naturelle de ces sols argileux, au sein du glissement de terrain, la mobilisation des minéraux de profondeur vers la surface augmente l'appréciation de leur fertilité par rapport au versant adjacent. L'Analyse des Correspondances Multiples (ACM) a montré que les exploitants sont très satisfaits de la mise en valeur des glissements lorsque les conditions naturelles favorables, reprises ci-dessus, y sont présentes. Et, les terres au sein de ces glissements de terrain sont plus chères par rapport aux terres adjacentes. La mise en valeur de glissements ayant des conditions moins favorables que les terres adjacentes ne peut se justifier que par la pression démographique pour l'accès aux terres cultivables.

L'étude a montré aussi que l'affectation des sols était différente dans et en dehors des glissements de terrain. L'analyse spatiale, plus quantitative, montre, par exemple, que la proportion de cultures (de subsistance et maraîchères) est beaucoup plus élevées au sein des glissements de terrain que sur les versants adjacents; ce qui est contraire aux études menée en Ardennes Flamande en Belgique (Van Den Eeckhaut et al., 2009) et en Pologne (Kroh, 2017) où l'intérieur des glissements de terrain est plus dédiée à la foresterie. Il nous semble que les contraintes anthropiques et les caractéristiques des glissements de terrain guident leur mise en valeur bien que ces zones soient plus ou moins à risque de futur aléa. Ces connaissances constituent une des clés maîtresses pour une meilleure planification des stratégies de réduction des risques aux glissements de terrain dans le contexte local et, en général, dans le milieu tropical montagneux.

5.2.3 *The disappearance of a disaster: vegetation cover change following a landslide – flash flood compound event in a human-influenced landscape of DR Congo*

Disparition d'une catastrophe : changement de la couverture végétale après un événement combiné glissement de terrain - crue éclair dans un paysage influencé par l'homme en RD Congo

Dans ce chapitre, une image Pléiades (situation au jour de l'événement) et 26 images Sentinel-2 ont permis de quantifier la vitesse du changement de la couverture végétale au sein des cicatrices de 92 zones sources de glissements de terrain superficiels et de 53 zones de transport-dépôt affectées par les coulées de débris-crues éclaires. Nous avons montré que (1) au jour de l'événement toutes les zones présentaient des cicatrices dont les valeurs de NDVI relatif étaient proches et (2) la vitesse de croissance est moins rapide dans les zones sources que dans les zones de transport-dépôt. Globalement, la végétalisation évolue positivement sur toutes les zones affectées mais sous la dépendance de facteurs environnementaux différents entre ces deux zones. En zones sources, sur les pentes fortes, la végétalisation est moins rapide (moins d'humidité, érosion du sol, etc.) ; en revanche les faibles pentes des zones de transport-dépôt sont plus favorables à la végétalisation (moins érosive, accumulation des sédiments, plus humide). En zones sources, la présence de la couverture forestière favorise une végétalisation rapide ; alors que la couverture forestière n'a aucun effet sur la végétalisation des zones de transport-dépôt. En condition naturelle, les zones sources peuvent ainsi se végétaliser rapidement, réduisant ainsi l'impact de la topographie. Dans les zones de transport-dépôt, les observations du terrain montrent que l'exploitation des matériaux laissés par les crues éclairs a laissé place aux plantations d'arbres et aux cultures. Les actions anthropiques (cultures, le passage du feu de brousse, le pâturage avec le piétinement des bétails, l'exploitation du sable ou des pierres) ont tout de même des impacts négatifs sur la végétalisation.

5.3 Les limitations

Le deuxième chapitre sur la catégorisation des processus de glissements de terrain et la distinction de leurs facteurs de prédisposition a abouti à des résultats originaux pour le monde tropical. Bien que l'inventaire soit détaillé, il est néanmoins incomplet, notamment pour les glissements de terrain superficiels car leur inventaire ne couvre que la période de la disponibilité des premières images © Google Earth. Par ailleurs, l'accès limité aux sources d'images satellitaires à hautes et très hautes résolutions, entre la période d'après les premières photographies aériennes et les premières images © Google Earth, n'a pas permis d'analyser la dynamique de certains glissements de terrain ou de constituer des inventaires pour différentes époques (e.g : Jones et al. 2021). L'interprétation visuelle de certains glissements de terrain dans des environnements perturbés, par les polycultures et sous forêt, peut engendrer des difficultés dans la cartographie exacte de leurs limites. Cependant, les ombres portées du modèle TanDEM-X à 5 m de résolution, à différentes orientations du Soleil, ont permis de limiter ces difficultés d'inventaire notamment pour les anciens glissements de terrain profonds. Les contraintes sécuritaires précaires lors de la validation de terrain n'ont pas permis de visiter toute la zone d'étude. Pour contourner ces contraintes, la validation de terrain a été conduite sur différentes sous-zones accessibles qui ont été sélectionnées aléatoirement suivant qu'elles présentaient de fortes ou faibles densités de glissements de terrain sur les images satellitaires. Mais aussi, le choix de ces sous-zones tenaient compte des différentes affectations du sol (celles en mosaïque de polycultures et celles plus monotones comme le pâturage). Les analyses des facteurs naturels ou anthropiques de prédisposition des différents glissements de terrain présentent encore certaines incertitudes, notamment, sur les conditions géo-environnementales dans la zone source ou proche qui peuvent ne pas être représentatives. En effet, il est certain que chaque rupture des pentes a eu lieu dans des situations différentes (climat, tectonique, altération, couverture végétale, etc.). Cette région du Rift est en constante mutation due à la sismicité régionale (Delvaux et al., 2017) et climatique (Ross et al., 2014). Ainsi, les facteurs topographiques calculés pour les anciens glissements de terrain, à partir de l'image radar SRTM (30 m de résolution), ne représentent pas nécessairement les conditions réelles d'occurrence pour chacun d'eux car ils sont des différentes époques. En effet, certains anciens glissements de terrain datent de centaines voire plusieurs milliers d'années lors du début du rifting (Dewitte et al., 2021). A titre d'exemple, les anciens glissements de terrain profonds le long du lac Kivu, dont les zones d'accumulation sont invisibles, témoignent de la fluctuation du niveau du lac due aux conditions climatiques et géologiques différentes (Ross et al., 2014; Dewitte et al., 2021). Le faible taux de prédiction des récents glissements de terrain profonds avec le modèle de susceptibilité des anciens glissements de terrain illustre bien que les facteurs de prédisposition évolueraient avec le temps.

Le troisième chapitre a renseigné sur les logiques des choix des différences d'affectations du sol entre l'intérieur d'un glissement de terrain et ses versants adjacents ; lesquels choix permettent d'analyser sur la présence des humains et/ou des exploitations des terres sur les glissements de terrain. L'étude constitue un jalon dans ce domaine. Cependant, nous pouvons dégager quelques limites, indépendantes de notre volonté qui, si elles étaient surmontées, renforceraient nos interprétations des résultats: (1) les conditions sécuritaires au moment de l'enquête n'ont pas permis de compléter les jeux de données; (2) le manque d'images Pléiades pour la période d'enquête à cause de la couverture nuageuse sur les images présentes durant la période de croissance des cultures ; les rares images à faible couverture nuageuse n'étaient disponibles que durant les périodes sèches (terres nues et jaunissement de plantes). Toutefois, il y a lieu de minimiser les incertitudes sur les affectations du sol obtenues de l'image Pléiades de novembre 2014 en ce sens que les affectations pérennes comme les bananiers, les eucalyptus, le pâturage et la forêt n'ont pas subi des profondes transformations entre novembre 2014 et août 2019 ; (3) les appréciations des conditions naturelles (fertilité, humidité, profondeur, etc.) et l'évaluation du prix du foncier ont été qualitatives au sein des glissements de terrain. Cependant, nous pouvons faire confiance aux avis des exploitants, sur leurs appréciations des conditions naturelles en place, car la majorité d'entre eux a une expérience de plus de 10 ans sur les utilisations des terres dans et en dehors des glissements de terrain.

L'étude sur le suivi du changement de couverture végétale, au quatrième chapitre, a permis de quantifier sur quelques années la temporalité et les facteurs environnementaux des tendances de la végétalisation des différentes zones affectées. Il s'agit l'une des contributions non négligeables sur la végétalisation post événement en milieu tropical et anthropisé. En revanche, le manque d'une série temporelle continue fait que, par exemple, il reste encore des inconnues sur la végétalisation pendant la première année qui a suivi l'événement. Cela est dû notamment à la mission Sentinel-2 dont les premières images datent de novembre 2015. L'utilisation d'images Sentinel-2 (à 10 m de résolution) a aussi fait que notre jeu de données n'a pris en compte que les zones affectées ayant plus de 0.1 ha ; il manque des informations sur la végétalisation de glissements de terrain de moins de 0.1 ha. Ainsi, seulement 15% de l'ensemble des zones sources (n=634) liées à l'événement d'octobre 2014 ont été étudiés. Les rôles de facteurs environnementaux ont été identifiés comme favorables ou non ; mais il y a encore beaucoup d'incertitudes quant à leurs impacts exacts sur la végétalisation. Seules des études complémentaires multi-approches (environnementale, pédologique, botanique, télédétection, etc.) peuvent renseigner sur la contribution de chaque facteur. Les observations continues du terrain sont ainsi un atout pour comprendre certaines subtilités de la végétalisation des différentes zones étudiées.

5.4 Principales implications et recommandations

Dans, le deuxième chapitre, les approches multi-méthodes pour l'inventaire des différentes catégories de glissements de terrain et les choix de prédicteurs à mettre dans les modèles de susceptibilité font partie des plus-values de cette étude. En ce qui concerne l'inventaire, l'étude a montré l'importance de : (1) la validation de terrain, souvent rare dans des nombreuses études ; (2) la validation est meilleure lors qu'elle est faite d'une façon détaillée sur différents environnements (anthropisé, moins perturbé, avec forte ou faible densité des glissements de terrain) et enfin (3) la différenciation des âges des glissements de terrain profonds à partir des interprétations sur des photographies aériennes historiques est aussi importante pour appréhender le contexte environnemental dans lequel ils ont évolué. Quant aux choix des prédicteurs à mettre dans chaque modèle de susceptibilité, notre étude : (1) recommande une sélection judicieuse qui dépend du bon sens de l'investigateur sur l'environnement dans lequel il mène son étude (contexte géomorphologique, des affectations du sol) ; (2) montre que la dynamique de la couverture forestière sur le long terme permet de comprendre les fréquences et les tailles des glissements de terrain superficiels suivant chaque environnement pour pouvoir ainsi expliquer les facteurs de leur prédisposition (par exemple dans les zones de forêt, l'occurrence de ces glissements de terrain est liée essentiellement aux facteurs naturels comme la topographie et la disponibilité du régolithe); (3) montre que la faible prédiction des glissements de terrain miniers sur tous les modèles de susceptibilité indique que leur présence répond à des conditions environnementales différentes des facteurs naturels d'occurrence des glissements de terrain; ce qui fait qu'ils se retrouvent sur des zones de faibles susceptibilités. Dans ce chapitre, en résumé, les analyses ont montré l'importance de (1) prendre en compte les activités humaines dans l'étude des facteurs de prédisposition des glissements de terrain ; d'autant plus nécessaire lorsqu'il y a des changements spatio-temporels associés à ces activités, (2) considérer la chronologie des glissements de terrain dans les évaluations de susceptibilités et de distribution.

Le troisième chapitre a abouti à la prise en considération des réalités locales pour comprendre pourquoi les gens vivent sur les glissements de terrain. Les enquêtes de terrain montrent bien que les populations locales connaissent bien ce qu'est un glissement de terrain, ses manifestations et savent identifier leurs causes dont la déforestation. Il est bien connu que les glissements de terrain représentent un risque majeur dans les environnements montagneux ruraux où les populations sont plus vulnérables vu leur précarité (Froude and Petley, 2018). Et, en milieu tropical dans les zones sujettes aux glissements de terrain, il est prévu que la pression anthropique (urbanisation non planifiée, changement d'affectations du sol etc.) va exposer les populations régulièrement sur les trajectoires des glissements de terrain car ces personnes occupent de plus en plus des terres marginales (Ozturk et al., 2022). L'étude de Maes et al. (2017) a montré qu'en Afrique, il y a un manque de mise en œuvre des stratégies de réduction de risque liés aux glissements de terrain. Les approches de notre étude peuvent aider, en amont, les chercheurs et les divers acteurs, œuvrant dans la planification des stratégies de réduction des risques aux glissements de terrain, de s'intéresser d'abord aux facteurs (caractéristiques et aux conditions naturelles en place) qui poussent les gens à vivre sur et/ou exploiter les glissements de terrain. Ainsi, ces connaissances peuvent aider, en aval, dans les propositions de stratégies de réduction des risques aux glissements de terrain. L'analyse spatiale et les enquêtes de terrain ont été des approches complémentaires sur la différenciation des mises en valeur entre l'intérieur et l'extérieur des glissements de terrain. La première approche aide à une compréhension globale quantitative et la seconde permet d'appréhender les différences suivant les réalités locales. Ainsi, par exemple, la plus grande proportion des cultures au sein des glissements de terrain illustre bien qu'en milieu montagneux, les conditions naturelles (faible pente, fertilité, sol profond et humide, etc.) sont autant de facteurs à prendre en compte lorsqu'on veut comprendre pourquoi les gens vivent sur les glissements de terrain.

Dans le quatrième chapitre, la quantification du changement de la couverture végétale à court termes a permis d'évaluer la vitesse et les facteurs environnementaux en lien avec la végétalisation. Hormis l'image Pléiades, le potentiel des images en accès libre et leurs analyses rapides dans Google Earth Engine ont prouvé la nécessité de les explorer pour trouver des réponses rapides sur l'étendue et le temps de la restauration de la couverture végétale. A la télédétection, il est primordial d'associer les observations continues sur le terrain. La combinaison de deux approches permet de retracer l'histoire du changement de la couverture végétale et d'estimer les types de risque à venir. Ainsi, par exemple, l'étude a montré que les zones sources se végétalisent moins rapidement. Cette plus faible vitesse de végétalisation est indicatrice des risques à venir dominés par des crues éclairs, si jamais un évènement pluvieux de même intensité, bien que rare, se reproduit. Le changement de la couverture végétale rapide des zones de transport-dépôt tient plus sur les aspects anthropiques où les matériaux mobilisés par les coulées de débris-crues éclairs ont été dégagés pour le besoin de vente ou reconstruction ; et ainsi, les zones dégagées ont été remises en cultures. Il n'y a que les observations de terrain qui peuvent renseigner sur ce genre de subtilités dans le changement de la couverture végétale des différentes zones.

5.5 Perspectives pour les recherches futures

Dans le deuxième chapitre, l'inventaire détaillé des différentes catégories de glissements de terrain constitue une cartographie de base des glissements de terrain à partir de laquelle d'autres inventaires, réalisés avec la même rigueur, pourront s'intégrer pour le monde tropical. A l'échelle régionale, l'inventaire doit être continu en y intégrant les nouveaux glissements de terrain qui apparaissent sur les images satellitaires et en cartographiant aussi les glissements de terrain observés uniquement sur le terrain. En ce qui concerne, les nouveaux glissements de terrain (isolés ou clusters) qui apparaissent, il y a lieu de tester leur taux de prédiction sur les modèles existants, surtout pour les glissements de terrain superficiels. Quant aux anciens glissements de terrain profonds nouvellement identifiés (terrain ou images satellites), il est aussi nécessaire de tester leur taux de prédiction sur le modèle de susceptibilité des anciens glissements de terrain. Pour les récents glissements de terrain profonds, avec un nombre suffisamment élevé et leur complétude, il convient d'établir leur modèle de susceptibilité ; ainsi, on pourrait, par exemple, mieux comprendre la nature évolutive des facteurs de prédisposition des anciens glissements de terrain profonds. C'est aussi le cas des modèles de susceptibilité pour les glissements de terrain liés aux routes et aux mines. D'un autre point de vue, notre étude a montré que la perte de la forêt et la distance aux routes (prise comme proxy de la présence humaine) ont un grand impact sur les occurrences des glissements de terrain superficiels ; ceci suppose d'approfondir les connaissances dans les stratégies de la préservation de la forêt afin de réduire les impacts de la dynamique de la couverture forestière future. Cette dernière pourra nous renseigner, par exemple, sur les contributions anthropiques et les impacts potentiels des changements climatiques en cours sur les occurrences des glissements de terrain à venir (Ozturk et al., 2022).

L'étude sur les logiques qui sous-tendent la mise en valeur des glissements de terrain, abordée au troisième chapitre, constituent un jalon pour des nombreuses recherches à l'échelle locale ou régionale. Des études comparatives pourront renforcer la littérature pour approfondir les discussions dans cette thématique. Pour ce qui est des conditions naturelles au sein des différentes caractéristiques de glissements de terrain, l'étude s'est limitée à une appréciation qualitative basée sur les réponses des exploitants. Cependant, il y a encore un manque d'actualisation des connaissances quantitatives sur les sols en place, en termes de fertilité, d'humidité, de profondeur, de teneur en sable ou de proportion en pierres entre l'intérieur des glissements de terrain et des versants adjacents. Les quelques études existantes sur les sols dans la région ont été réalisées à des altitudes proches du lac Kivu, en dehors des glissements de terrain ou encore sur des localisations non précises (Pecrot and Leonard, 1960; CIALCA, 2008; Muliele Muku, 2014; Munyahali, 2018). Quelques-unes des pistes d'études seraient : (1) d'aborder la même étude avec les mêmes méthodologies dans des environnements similaires au nôtre et sur des mêmes échelles ; (2) d'initier des études quantitatives détaillées sur les profils des sols au sein des glissements de terrain afin d'évaluer les paramètres tels que la fertilité, la profondeur, la teneur en sable, la proportion de pierres etc. par rapport aux terres adjacentes (Van Eynde et al., 2017) ; (3) des études comparatives quantitatives sur le rendement des différentes affectations du sol et l'évaluation économique des terres au sein des glissements de terrain et par rapport aux terres des versants adjacents ; (4) les caractéristiques des glissements de terrain favorables à la mise en valeur étant connu, des études pourraient être menées dans le cadre de la gestion des terres basée sur les connaissances locales ; (5) enfin, à l'échelle locale ou d'un bassin versant, l'acquisition d'images à très hautes résolutions, grâce aux capteurs embarqués sur un drone, est une des solutions efficaces pour contourner le manque d'images à très haute résolution lié à la présence de la couverture nuageuse. Les images à très hautes résolutions peuvent permettre d'étudier les affectations du sol à l'échelle des cultures au moment de l'enquête de terrain. Ces diverses études pourraient renforcer les connaissances sur les facteurs qui influencent la présence humaine sur les glissements de terrain qui restent, par ailleurs, des zones instables ou potentiellement à risque dans le futur. Ainsi, des stratégies de gestion de risque pourraient être proposées en termes des pratiques culturales sur les zones instables et la réduction des expositions.

Dans le quatrième chapitre, l'étude a montré que, sur le court-terme, la vitesse du changement de la couverture végétale évolue positivement dans les zones affectées par des évènements combinés glissements de terrain et coulée de débris-crues éclairs. Les facteurs du changement de la couverture végétale sont connus ; cependant, vu la limitation des moyens techniques et financiers des pays en développement, il est très difficile d'agir sur les facteurs topographiques. Le rôle de la présence de la couverture forestière étant connu comme favorable au changement de la couverture végétale des zones sources, des études devraient être menées dans le cadre des pratiques agricoles (par exemples : cultures en terrasse avec bande enherbée aux limites, terrassement, etc.) qui permettent la stabilité des pentes. Pour le suivi d'ensemble de la végétalisation à l'échelle locale ou de bassin versant, des images à très hautes résolutions devraient être produites par divers capteurs embarqués sur le drone. Pour la végétalisation, on peut ainsi quantifier la croissance en hauteur et en largeur des plantes. Il serait aussi essentiel de comparer, pour un même événement ou deux, la vitesse du changement de la couverture végétale entre les milieux forestiers et les zones anthropisées afin d'examiner le poids de chaque facteur de prédisposition.

5.6 Implications locales et sociétales de l'étude

La recherche doctorale nous a renseigné suffisamment sur le fait que, dans le contexte anthropique, le milieu rural des versants du Rift à l'ouest du lac Kivu est confronté à des changements environnementaux importants et qui l'exposent aux risques liés aux glissements de terrain. Sur le plan local, il y a lieu de réfléchir sur les actions à mener sur le terrain dans la gestion et la réduction des risques de catastrophes liée aux glissements de terrain. La récurrence de ces catastrophes, dont la plupart sont non médiatisées, mérite une attention particulière auprès des différents acteurs. Il s'agit, par exemples, d'un renforcement des compétences scientifiques, et de la capacitation des organismes non-gouvernementaux locaux et des services étatiques (protection civile, service de l'environnement, service des voiries, etc.). La mise en œuvre de ces stratégies ne peut être efficace que dans les collaborations multidisciplinaires. A partir de la base des données constituées, la cartographie détaillée des différentes catégories de glissements de terrain (par des polygones) et les cartes de susceptibilités peuvent servir d'aide à la décision pour l'implantation des nouvelles infrastructures de base comme les lignes électriques, les routes, les bâtiments scolaires et les villages. Dans la mise en valeur des glissements de terrain, les exploitants devront être sensibilisés en matière de risques suivant les caractéristiques et les conditions naturelles en place. Pour les récents glissements de terrain dont les cicatrices sont encore fraîches, il serait mieux d'orienter leurs utilisations pour la sylviculture.

Le rôle de la déforestation et d'autres formes de pression anthropiques ont été reconnus comme facteurs importants des occurrences des glissements de terrain et même une contrainte à leur végétalisation. L'implication des différents acteurs de terrain est indispensable pour réduire la déforestation sur les zones les plus sensibles comme les pentes fortes et pour adapter les utilisations de terre en milieu montagneux (exemple : mode des cultures en terrasse). Notre étude a montré que sur les zones les plus sensibles, la déforestation joue un grand rôle dans l'occurrence des glissements de terrain superficiels. Dans le contexte local, l'action humaine a une faible marge de manœuvre pour une adaptation par rapport aux facteurs topographiques (drainage, mur de soutènement, etc.). Ainsi, les autorités étatiques, les organismes humanitaires œuvrant sur les aspects environnementaux, les populations locales et les scientifiques devront mener, en synergie, des actions concrètes dans la restauration et la préservation du couvert forestier. Les zones les plus sensibles seront ainsi préservées à travers un plan d'aménagement des villages adaptés aux zones sujettes aux glissements de terrain. En ce qui concerne les glissements de terrain liés aux mines, des efforts devraient être menés dans l'application des cadres légaux en matière de préservation de la couverture forestière notamment en appliquant le code minier (Article 42 : De l'instruction environnementale et sociale , Cabinet du Président de la République, 2018). En effet, l'exploitation artisanale des minerais a lieu, de plus en plus, dans les forêts et cela s'accompagne de coupes massives (Rapport UNESCO, https :// whc.unesco.org/fr/soc/2465/, consulté le 18 janvier 2023).

Une des sources majeures de la déforestation sur le long terme est l'utilisation du bois comme principale source d'énergie pour des millions de personnes de la région notamment pour les deux grandes villes Goma et Bukavu. Il est primordial d'envisager dans le court et moyen terme une conversion énergétique.

La recherche doctorale a permis des échanges d'expériences continues avec les non-professionnels et les scientifiques locaux pour collecter les données sur les glissements de terrain et discuter des stratégies de réduction de risque suivant les réalités locales. Ainsi, durant la recherche doctorale, nous avons bénéficié des collaborations des chefs de village et des nombreuses autres personnes clés avec qui nous sommes en contacts réguliers. Ces personnes ressources renseignent mensuellement, par téléphone, sur les activités liées aux glissements de terrain et d'autres catastrophes similaires dans le cadre du Projet RESIST (https://resist.africamuseum.be/homepage, consulté le 20/10/2022). Ces collaborations continuent dans le cadre du Projet HARISSA et elles sont renforcées avec la mise place d'un réseau d'observateurs citoyens (https://georiska.africamuseum.be/fr/ activities/harissa, consulté le 20/10/2022). Les observateurs citoyens collectent des informations sur tout événement lié aux catastrophes naturelles, dont les glissements de terrain, sur une large zone par rapport à notre zone d'étude initiale. Les collectes de données se font grâce à un formulaire intégré sur l'application KoboToolbox installée sur une tablette de terrain. Pour le volet scientifique, la dissémination des connaissances s'est faite à travers de nombreux séminaires, conférences et webinaires. C'étaient des occasions de discussions interactives sur différents sujets de notre thèse. Les publications scientifiques servent et serviront aussi à disséminer les connaissances sur la problématique des glissements de terrain dans la région. Outre les aspects scientifiques de dissémination des connaissances, les résultats de notre recherche doctorale sont aussi présentés dans des Newsletters et les médias locaux dans le cadre du Projet HARISSA (https://georiska.africamuseum.be/fr/activities/harissa; consulté le

20/10/2022). Des nombreuses données collectées à travers cette thèse peuvent servir de recherches futures à tous les niveaux de l'enseignement universitaire.

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Appendices

Appendix A

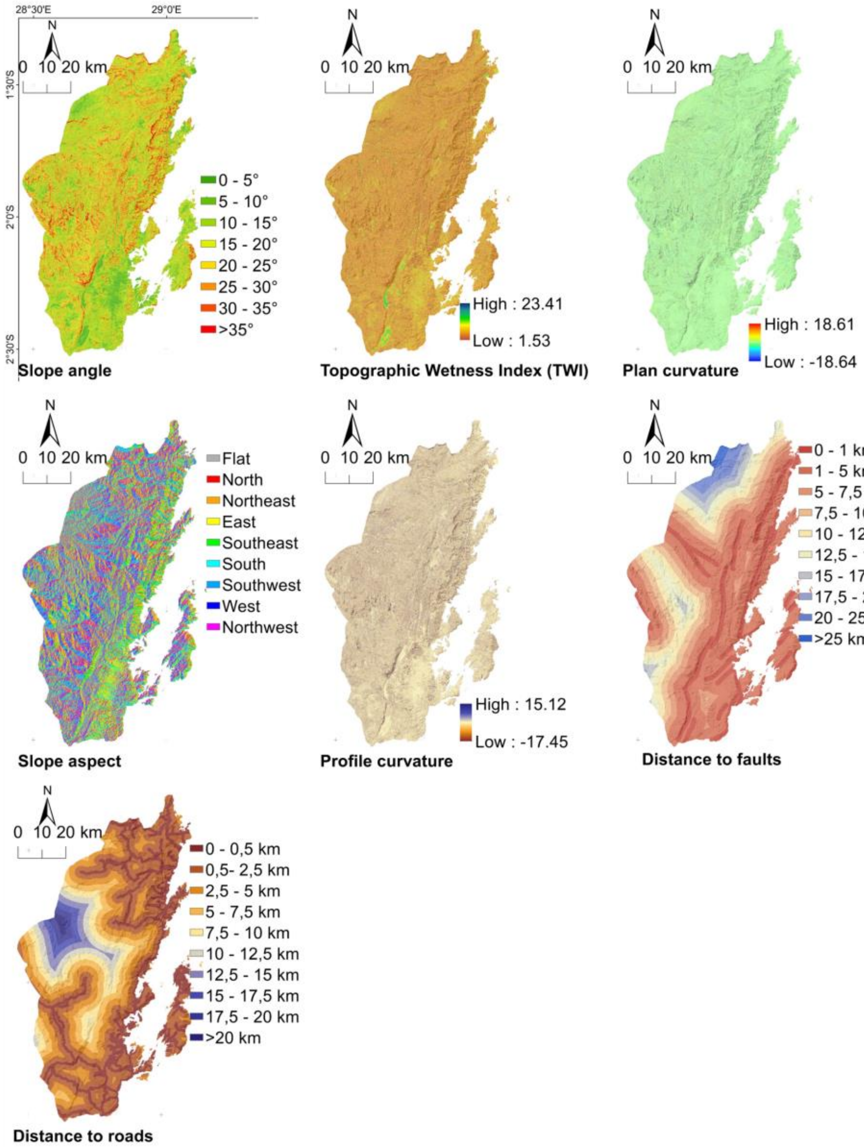

Figure A. 1*: Additional predisposing factors used for the susceptibility assessment not shown in the manuscript.*

Appendix B

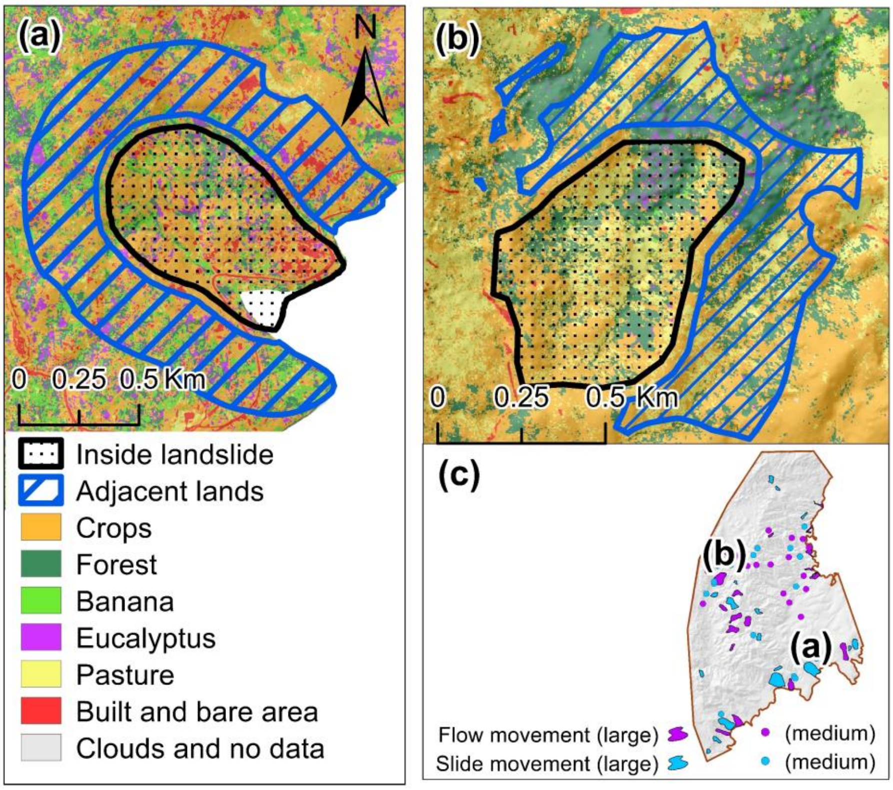

Figure B. 1*: (a and b) Definition of the two distinct zones: inside and outside landslides. (c) Landslides selected by stratification criteria*

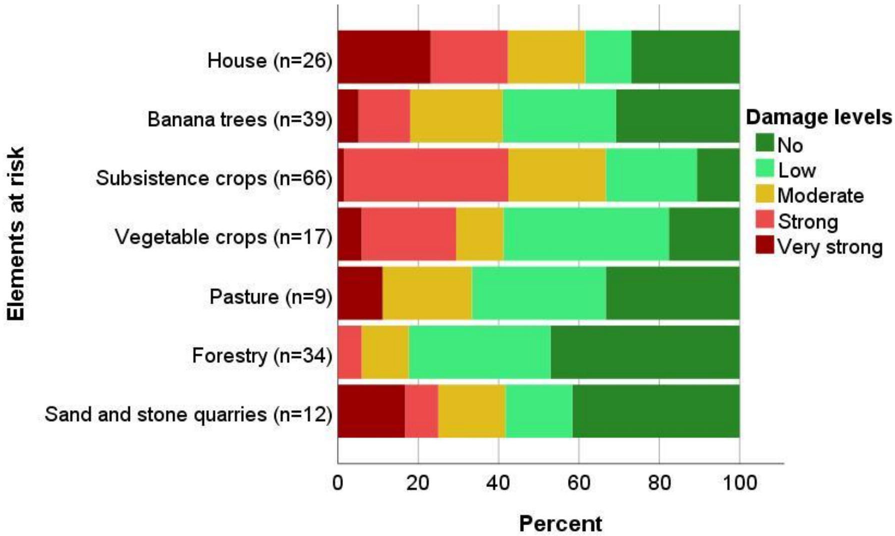

Figure B. 2: *Elements at risk and damage levels within landslides. The number of surveyed people (n) reporting a given element at risk is provided in parentheses.*

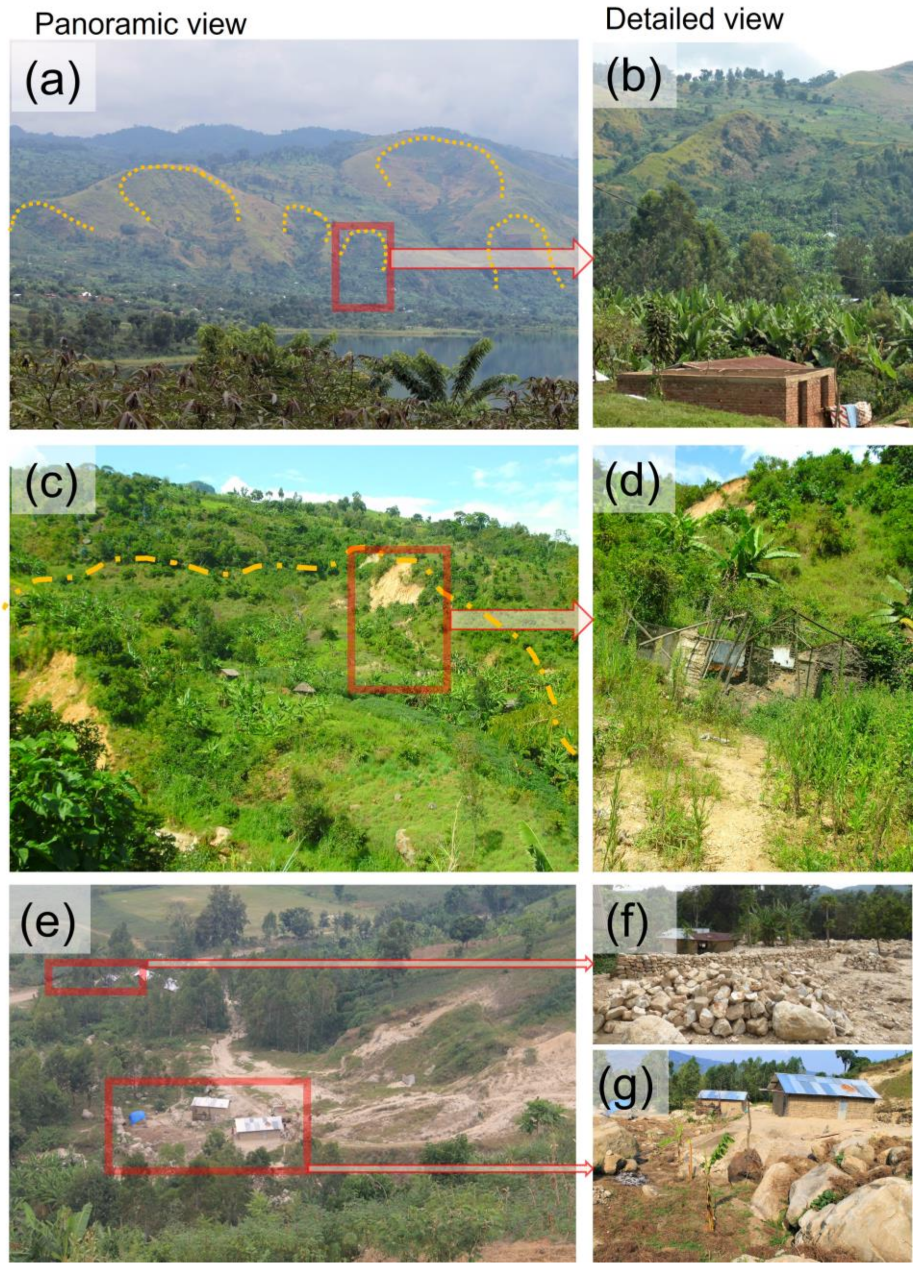

Figure B. 3: *Valorization of different types of landslides. a & b) Old deep-seated landslides (various crops, banana plantations, entire village; -2.143°S, 28.854°E); c & d) Recent deep-seated landslide (food crops, banana plantations, houses destroyed* *by landslide activity; -2. 013°S, 28.896°E); e, f & g) rebuilt village in Rambira after debris flow/flash flood in October 2014, sand and stone mining from debris deposits (f: sale of stone blocks and g: new construction and young banana plantlets; -2.044°S, 28.898°E).*

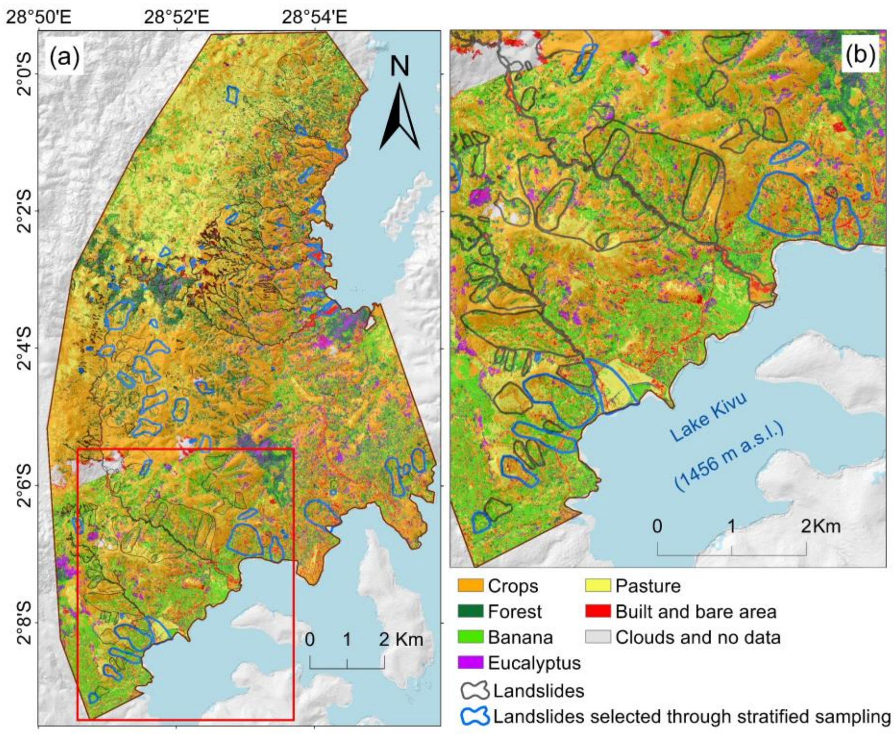

Figure B. 4:*(a) Land uses from supervised classification of the Pléiades (2014) image at 2 m resolution (Overall Accuracy = 97%, Kappa Coefficient = 0.92). (b) Zoom of land uses inside and outside the landslides. The landslides delineated in blue were used for the spatial analysis.*

Table B.1: Areas (ha) concerned by the spatial analysis according to the stratified classification

Movement	Size	Downstream position (< 1700 m)			Upstream position (> 1900 m)		
		Inside (ha)	Outside (ha)	Subtotal (ha)	Inside (ha)	Outside (ha)	Subtotal (ha)
Flow	Large (5 – 100 ha)	132.9	162.3	295.2	103.4	134.7	238.1
	Medium (0.1 -1 ha)	1.8	15.7	17.4	2.7	12.0	14.6
Slide	Large (5 – 100 ha)	227.9	235.0	462.9	402.7	426.5	829.3
	Medium (0.1 -1 ha)	4.5	16.3	20.7	6.5	11.9	18.5
	Total	367.1	429.2	796.3	515.3	585.1	1100.5

Table B.2: Summary of the different tests applied, their meaning, the formula and common uses

Statistic test	**Meaning**	**Hypotheses**	**Formula**	**Common uses**
Chi-Square Test of Independence	This test utilizes a contingency table to analyze the data. A contingency table (also known as a cross-tabulation, crosstab, or two-way table) is an arrangement in which data is classified according to two categorical variables.	H_0: "[*Variable 1*] is independent of [*Variable 2*]" H_1: "[*Variable 1*] is not independent of [*Variable 2*]" OR H_0: "[*Variable 1*] is not associated with [*Variable 2*]" H_1: "[*Variable 1*] is associated with [*Variable 2*]"	$$x^2 = \sum_{i=1}^{R}\sum_{j=1}^{C}\frac{(O_{ij} - e_{ij})^2}{e_{ij}}$$ Where O_{ij} is the observed cell count in the i^{th} row and j^{th} column of the table Oe_{ij} is the expected cell count in the i^{th} row and j^{th} column of the table	The Chi-Square Test of Independence is commonly used to test the following: • Statistical independence or association between two categorical variables.
Spearman's Rank Correlation	The Spearman's Rank Correlation Coefficient Rs value is a statistical measure of the strength of a link or relationship between two sets of data.		The coefficient (R_s) is calculated on this calculator using the common formula: $$R_s = 1 - \left(\frac{6\Sigma d^2}{n^3 - n}\right)$$ The answer will always be between 1.0 (a perfect positive correlation) and -1.0 (a perfect negative correlation). An R_s of 0 indicates no association between ranks.	Spearman's Rank has many common uses in geography including

<table>
<tr><td></td><td colspan="2"></td><td></td><td></td></tr>
<tr>
<td>Paired samples t Test</td>
<td>The Paired Samples t Test compares the means of two measurements taken from the same individual, object, or related units.</td>
<td>H$_0$: $\mu_1 = \mu_2$ ("the paired population means are equal")
H$_1$: $\mu_1 \neq \mu_2$ ("the paired population means are not equal")
OR

H$_0$: $\mu_1 - \mu_2 = 0$ ("the difference between the paired population means is equal to 0")

H$_1$: $\mu_1 - \mu_2 \neq 0$ ("the difference between the paired population means is not 0")

where

• μ1 is the population mean of variable 1, and

• μ2 is the population mean of variable 2.</td>
<td>$$t = \frac{\bar{x}_{diff} - 0}{S_{\bar{x}}}$$
Where $S_{\bar{x}} = \frac{s_{diff}}{\sqrt{n}}$

Where:
• S_{diff}= Sample mean of the differences
n = Sample size (i.e., number of observations)

• S_{diff}= Sample standard deviation of the differences

• $S_{\bar{x}}$ = Estimated standard error of the mean (s/sqrt(n))</td>
<td>• To compare unpaired means between two independent groups on a continuous outcome that is normally distributed, choose the Independent Samples t Test.
• To compare unpaired means between more than two groups on a continuous outcome that is normally distributed, choose ANOVA.

• To compare paired means for continuous data that are not normally distributed, choose the nonparametric Wilcoxon Signed-Ranks Test.

• To compare paired means for ranked data, choose the nonparametric Wilcoxon Signed-Ranks Test.</td>
</tr>
<tr>
<td>Multiple</td>
<td>Multiple</td>
<td colspan="2">Data Table. The analyzed (raw) data table in this case is formed by multiple</td>
<td>Studying the variables</td>
</tr>
</table>

correspondence analysis	Correspondence Analysis (MCA) is the generalization of (simple) correspondence analysis to the case when we have more than two categorical variables.	categorical variables. This table can be transformed into a complete disjoint table, or into a Burt table crossing all variables two-by-two). This analysis can also be regarded as a generalization of a normalized PCA for a data table of categorical variables.		• Links between qualitative variables (in relation to the categories) • Visualization of the set of associations between categories • Synthetic variables (quantitative indicators based on the qualitative variables).
Linear regression model	In linear regression we usually have many different values of the explanatory variable, and we usually assume that values between the observed values of the explanatory variables are also possible values of the explanatory variables..	We postulate a linear relationship between the land use difference proportion mean and the landslide characteristics	$y_i = b_0 + b_1 x_1 + e_i$ Where $\boxed{i}$ is an observation (e.g.: landslide characteristics) y_i is the dependent or outcome variable (difference in proportion) The term b_0 is the intercept, b_1 is the regression coefficient, and e_i is the residual for each landslide characteristic.	When we are examining the relationship between a quantitative outcome and a single quantitative explanatory variable, simple linear regression is the most com-monly considered analysis method.

Table B. 3: *Non-parametric correlation (Spearman's rho) between landslide characteristics (n=67) (p-value: ** < 0.01)*

	Age	Position	Lithology	Movement	Depth	Size
Age	**1**	-0.08	-0.09	0.52**	0.97**	0.40**
Position		**1**	0.03	-0.02	-0.11	-0.02
Lithology			**1**	-0.22	-0.07	-0.01
Movement				**1**	0.55**	-0.01
Depth					**1**	0.37**
Size						**1**

Table B. 4: *Farmer's satisfaction levels according to landslide characteristics and Chi-square test result.*

		Unsatisfied (%)	Little satisfied (%)	Moderately satisfied (%)	Very satisfied (%)	Total (%)	Chi-square tests
Position	Downstream	45	65	59	57	57	0.58
	Upstream	55	35	41	43	43	
Landslide size	Medium	65	27	45	14	39	**0.01**
	Large	35	73	55	86	61	
Movement	Flow	75	58	41	50	56	0.15
	Slide	25	42	59	50	44	
Age	Recent	75	38	27	36	44	**0.01**
	Old	25	62	73	64	56	
Landslide depth	Shallow	70	35	27	21	39	**0.01**
	Deep-seated	30	65	73	79	61	
Lithology	Pelites	25	35	73	57	46	**0.008**
	Granite	75	65	27	43	54	

***Table B. 5**: Influence of landslide characteristics on the cultivation of banana plants, vegetable crops, subsistence crops or coffee. For each characteristic, farmers are divided into two groups: those who do not grow the crop ('No', left) and those who do grow the crop ('Yes', right). The values in the table correspond to the number of farmers who answered Yes or No. Significative p-values of Chi-square tests are in bold.*

		Banana			Subsistence crop			Vegetable crop			Forestry			Pasture			Coffee			Other activities		
		No	Yes	Total	No	Yes	Total	No	Yes	Total	No	Yes	Total	No	Yes	Total	No	Yes	Total	No	Yes	Total
Age	Recent	22	14	36	13	23	36	32	4	36	21	15	36	32	4	36	33	3	36	27	9	36
	Old	21	25	46	4	42	46	33	13	46	27	19	46	41	5	46	39	7	46	43	3	46
Total		43	39	82	17	65	82	65	17	82	48	34	82	73	9	82	72	10	82	70	12	82
p-value of Chi-square tests				0.164			**0.002**	0.057					0.974			0.972			0.344			**0.019**
Position	Downstream	21	26	47	9	38	47	34	13	47	27	20	47	42	5	47	40	7	47	42	5	47
	Upstream	22	13	35	8	27	35	31	4	35	21	14	35	31	4	35	32	3	35	28	7	35
Total		43	39	82	17	65	82	65	17	82	48	34	82	73	3	82	72	10	82	70	12	82
p-value of Chi-square tests				0.105			0.682	0.073			0.816					0.910			0.387			0.235
Lithology	Pelites	16	22	38	3	35	38	24	14	38	22	16	38	34	4	38	30	8	38	35	3	38
	Granite	27	17	44	14	30	44	41	3	44	26	18	44	39	5	44	42	2	44	35	9	44

Total		43	39	82	17	65	82	65	17	82	48	34	82	73	9	82	72	10	82	70	12	82
p-value of Chi-square tests				0.082			**0.008**			**0.001**			0.913			0.904			**0.023**			0.109
Mouvement	Flow	31	15	46	15	31	46	40	6	46	28	18	46	39	7	46	43	3	46	37	9	46
	Slide	12	24	36	2	34	36	25	11	36	20	16	36	34	2	36	29	7	36	33	3	36
Total		43	39	82	17	65	82	65	17	82	48	34	82	73	9	82	72	10	82	70	12	82
p-value of Chi-square tests				**0.0002**			**0.003**			**0.048**			0.628			0.165			0.076			0.153
Landslide depth	Shallow	24	8	32	14	18	32	28	4	32	19	13	32	26	6	32	29	3	32	22	10	32
	Deep-seated	19	31	50	3	47	50	37	13	50	29	21	50	47	3	50	43	7	50	48	2	50
Total		43	39	82	17	65	82	65	17	82	48	34	82	73	9	82	72	10	82	70	12	82
Chi-square tests				**0.001**			**0.000**		0.141				0.902			0.072			0.532			0.001
Landslide size	Medium	20	12	32	9	23	32	29	3	32	19	13	32	27	5	32	30	2	32	24	8	32
	Large	23	27	50	8	42	50	36	14	50	29	21	50	46	4	50	42	8	50	46	4	50
Total		43	39	82	17	65	82	65	17	82	48	34	82	73	9	82	72	10	82	70	12	82
p-value of Chi-square tests				0.144			0.186			**0.042**			0.902			0.281			0.188			**0.034**

Table B. 6: *Summary of linear regression models of differences in proportions (inside - outside) of different land uses inside and outside landslides according to landslide characteristics (p-value: * < 0.05, ** < 0.01, ***< 0.001). For a given land use (e.g., Forest), a positive coefficient indicates that the difference in proportion (inside – outside) is greater for the listed landslide characteristic (e.g., Forest - Slide) than for the reference condition (e.g., Forest - Flow). See materials and methods section for transformations applied to the variables before statistical analysis.*

	Dependent variable	Crops	Forest	Banana	Eucalyptus	Pasture
Model summary	ANOVA (F)	8.04***	5.36***	4.26**	1.31	2.73*
	R^2	0.40***	0.31***	0.26**	0.10	0.18*
Model coefficients (β)	(Constant)	0.40***	-0.15**	-0.03*	-0.05*	-0.14*
Predictors	Upstream	0.05	0.03	0.02	-0.01	-0.09*
	Large	-0.10	0.08*	-0.04	0.04	0.02
	Slide	-0.18*	0.10*	0.01	0.04	0.01
	Old	-0.22*	0.04	0.10**	-0.03	0.08
	Granites	-0.06	-0.04	-0.02	0.01	0.10*

Reference modalities for predictors are: position = downstream; size = medium; movement = flow; age = recent; lithology = pelites.

Table B.7: QUESTIONNAIRE D'ENQUÊTE SUR LES MISES EN VALEURS DE GLISSEMENTS DE TERRAIN

Objectif de l'enquête : comprendre les logiques de la mise en valeur des glissements de terrain par des enquêtes auprès des ménages vivant ou exerçant une activité dans le glissement de terrain à Kalehe (villages entre Nyambasha et Bushushu).

I. Informations générales

Numéro Point GPS	
Numéro photos sur site	………………/……………………………………..
Identifiant Glissement de terrain	
Village	
Date : …/………. /20…	Heure : début…………… Fin : ……………………

II. Connaissances sur le glissement de terrain

2.1. Savez-vous ce qu'est un glissement de terrain ? ***Commentaires***		- Oui - Non
2.2. Avez-vous déjà observé des glissements de terrain ? ***Donnez un exemple***		- Oui - Non
2.3. Avez-vous conscience que vous exercez votre activité sur un glissement de terrain ?		- Oui - Non
2.4. Si oui en 1.1, savez-vous quand est-ce que ce glissement de terrain a eu lieu ? ***Comparer la période d'arriver sur le site et l'occurrence du glissement de terrain***	1. Moins de 1 an 2. 1 à 2 ans 3. 3 à 5 ans	4. 6 à 10 ans 5. Plus de 10 ans 6. Je ne sais pas
2.5. Depuis combien d'année exercez-vous vos activités sur ce site ?	1. Moins de 1 an 2. 1 à 2 ans 3. 3 à 5 ans	4. 6 à 10 ans 5. Plus de 10 ans
2.6. Qu'est-ce qui vous a motivé à venir vous installer à cet endroit précis ? ***Enquêté donne lui-même ses motivations pour l'occupation. Plusieurs réponses possible***	- Achat d'un terrain accessible à mon budget - Héritage familial - Racine coutumière - Coût de location favorable - Parcelle donnée gratuitement - Sol productif - Faire face aux besoins familiaux□	
2.7. Au moment de vous installer sur ce site, aviez-vous conscience qu'il s'agissait d'un glissement de terrain ?		- Oui - Non
2.8. Si oui en 1.7, comment estimiez-vous le risque de dégât dû au glissement à votre propriété au moment de votre installation ?		1. Nul 2. Faible 3. Elevé

	4. Très élevé
2.9. Et actuellement, comment estimiez-vous le risque de dégât dû au glissement à votre propriété ?	1. Nul 2. Faible 3. Elevé 4. Très élevé
2.10. Comment estimiez-vous le coût économique relatif de votre terrain dans le glissement par rapport à terrain situé sur le versant ? ***Donner les assertions***	1. Beaucoup plus cher 2. Plus Cher 3. Pareil 4. Moins cher 5. Beaucoup moins cher
2.11. De manière générale, comment se présente le prix d'un terrain dans le glissement de terrain par rapport au terrain situé sur le versant ?	- Beaucoup plus cher - Plus Cher - Pareil - Moins cher - beaucoup moins cher
2.12. Si vous avez répondu (beaucoup) plus cher / moins cher en 1.10, Pouvez-vous me parler des facteurs qui affectent le prix de votre terrain dans le glissement de terrain ***Entourer la bonne réponse*** ***Ne pas lire les assertions, plusieurs réponses peuvent être cochées***	- topographie : plus / moins - Disponibilité en eau : plus / moins - Fertilité : meilleure / moins bonne - Pierrosité : plus forte / moindre - Cultures toute l'année - Convient pour les bananiers - Abondances de sable - Sol profond - Autres (à préciser)…..
Impacts du glissement de terrain sur l'exploitation	
2.13. Est-ce que ce glissement de terrain est actif ? ***L'enquêteur indique si le glissement est actif suivant ses propres observations***	- Oui - Non
2.14. Si oui. Quels sont les signes de glissement que vous observez sur ce site ? ***L'enquêteur cherche à comprendre si l'exploitant observe l'activité de ce glissement de terrain dans son site ?***	- Des déformations dans le champ - Des inondations - Chutes de blocs - Inclinaison des cultures et des arbres - Fissures dans les murs des maisons - Autres …… ;

2.15. Quels sont les éléments de votre exploitation qui subissent des dégâts (impacts négatifs) suite au glissement ?	Facteurs affectés		Nul	Faible	Moye	Fort	Trèsfort
	Maison						
	Justif. :						
	Bananier						

- ***(1) Indiquer les facteurs affectés.*** - ***(2) Donnez l'échelle d'appréciation***	Justif. :						
	Cultures vivrières						
	Justif. :						
	Cultures maraîchères						
	Justif. :						
	Pâturage élevage						
	Justif. :						
	Sylviculture						
	Justif. :						
	Pisciculture						
	Justif. :						
	Carrière de sable						
	Justif. :						
	Carrière de pierre						
	Justif. :						
	Autres…… 1………. 2…………						
Le point 1.15 sera illustré par des croquis							

III. Facteurs influençant la mise en valeur du glissement de terrain

3.1. Avez-vous plusieurs parcelle	- Oui - Non
3.2. Quelle est la superficie totale de votre exploitation ?	-

	C'est une question sensible, je ne donne pas
3.3. Quelle est la superficie de votre exploitation dans le glissement ***Si nécessaire mesure par GPS***	- - C'est une question sensible, je ne donne pas
3.4. Quelle est la part de votre exploitation dans le glissement relatif à l'ensemble de vos superficies ? ***A ne pas poser si l'enquêté a répondu aux questions 2.3 & 2.4***	1. 25% 2. 50% 3. 75% 4. 100%

3.5.	Activités	Dans le glissement de terrain		En dehors du glissement	
		Tout	Principale	Tout	principale
Pouvez-vous me lister les activités que vous exercez dans le glissement et en dehors (si applicable) ? ***Indiquer également l'activité principale***	- Bananier				
	- Cultures vivrières				
	- Cultures maraichères				
	- Pâturage élevage				
	- sylviculture				
	- Pisciculture				
	- Carrière de sable				
	- Carrière de pierre				
	- Restauration & commerce				
	- Autres…………….. 1… 2… 3… 4…				

3.6. Y-a-t-il des cultures que vous pratiquez préférentiellement dans le glissement de terrain par rapport aux cultures en dehors du glissement de terrain ? ***L'enquêté liste cinq cultures maximums***	1)…. 2)… 3)…. 4)….. 5)…. Pourquoi ? 1) 2) 3)

<table>
<tr><td colspan="4"></td><td colspan="2">4)

5)</td></tr>
<tr><td colspan="6">3.7. Comment se présente le rendement par rapport à un terrain en dehors du glissement ?</td></tr>
<tr><td>Cultures pratiquées</td><td>Moins bon</td><td>Meilleur</td><td colspan="3">Pourquoi ? (indiquez 1, 2, 3, 4, 5 etc.). Plusieurs réponses possibles</td></tr>
<tr><td>a. ………</td><td></td><td></td><td colspan="3"></td></tr>
<tr><td>b. ………</td><td></td><td></td><td colspan="3"></td></tr>
<tr><td>c. ………</td><td></td><td></td><td colspan="3"></td></tr>
<tr><td>d. ………</td><td></td><td></td><td colspan="3"></td></tr>
<tr><td>e. ………</td><td></td><td></td><td colspan="3"></td></tr>
<tr><td>f. ……….</td><td></td><td></td><td colspan="3"></td></tr>
<tr><td colspan="6">- Fertilité du sol 1 - Trop sec 3
- Trop humide 2 - Terrain en replat 4
- Pierrosité 5 - Aucune pensée à guider mon choix 6
- Autres 7</td></tr>
<tr><td colspan="3">3.8. Pourquoi exercez-vous les exploitations de matériaux de construction à cet endroit ?

<u>Voir question 2.5.</u> Si l'activité principale est l'exploitation de carrière. Demander pourquoi il exerce cette activité à cet endroit et l'agriculture dans l'autres</td><td colspan="3">- Gisement ancien
- Position près de la route & lac
- Abondance de pierre & sable issus de la couleé de débris
- Gain économique rapide
- Autres :….</td></tr>
<tr><td colspan="3">3.9. Combien des personnes employez-vous dans ce site ?

Plus d'une proposition possible</td><td colspan="3">- Je travaille seul
- Moi et ma femme
- Toute la famille
- Journaliers engagés
- Autres (à préciser) :</td></tr>
<tr><td colspan="2">3.10. Statut de l'exploitation</td><td colspan="2">1. Domaine privé
2. Héritage familial
3. Métayage
4. Site abandonné</td><td colspan="2">5. ONG
6. Don d'un notable
7. Association paysanne
8. Propriété de l'Etat
9. Aucune réponse</td></tr>
<tr><td colspan="3">3.11. stimez la distance que vous parcourez pour atteindre ce site

Lire les différentes propositions</td><td colspan="3">1. J'habite sur place
2. moins de 1 km
3. 1 à 5 km
4. Plus de 5 km</td></tr>
</table>

3.12. Combien de temps que vous passez pour atteindre ce site ?	- J'habite sur place
3.13. Quel type de route permet l'accès au site d'exploitation ?	- Route principale - Route secondaire - Chemin de champs

Organisation de l'exploitation

3.14.	**Propositions**	**Modalités**	**1.Aucun effet**	**2.Avantages**	**3.Désavantages**
Pourriez-vous me lister les avantages ou désavantage pour votre activité principales (voir 2.5) du fait de se trouver dans un glissement de terrain par rapport à une parcelle située sur le versant juste en dehors du glissement ? ***L'enquêteur donne à l'enquêté les propositions qui à***	Pente	Plus Forte			
		Équivalente			
		Plus faible			
	Fertilité du sol	Meilleure			
		Equivalente			
		Moindre			
	Profondeur du sol	Plus profond			
		Equivalent			
		Plus faible			
	Humidité	Plus forte			
		Equivalente			
		Plus Faible			
	Présence de pierre	Plus Forte			
		Équivalente			
		Plus faible			
	Présence de sable	Plus Forte			
		Équivalente			
		Plus Faible			

son tour donne ses avis par rapport aux avantages, désavantages et aucun effet de chaque proposition.	Autres : 1…. 2…. 3…. 4….				

Gestion des sols

3.15. Pratiquez-vous des aménagements de stabilisation des glissements de terrain	1. Oui 0. Non

	Dispositifs	Présence	Si oui, Niveau de satisfaction			
			1.Très satisfait	2.Satisfait	3.Faiblement satisfait	4.Pas du tout
3.16. **Si oui**, Quels sont les modes de lutte que vous pratiquez pour stabiliser les versants ***Ne pas préciser les réponses à l'enquêté***	Cultures sur terrasse	- Oui - Non				
	Végétalisation des versants instables	- Oui - Non				
	Traçages des canaux d'évacuation des eaux	- Oui - Non				
	Bandes enherbées	- Oui - Non				
	Paillage_feuilles (bananier…)	- Oui - Non				
	Autres (à préciser) …………………..					

3.17. **Si non**, quelles sont les raisons ***Question se rapportant à la question 2.13.***	1. Aucune connaissance de techniques utiles 2. Maitrise insuffisante des techniques 3. Responsabilité de l'Etat 4. Coût financier élevé pour le réaliser 5. Trop de travail 6. Autres :………………………………………

3.18. Comment avez-vous connaissance de ces modes de lutte	1. à l'école 2. campagne de formation des ONG 3. moniteur agricole du village 4. chef du village 5. observation individuelle du terrain 6. Voisins de champs 7. Parents 8. Autres (à préciser)……………………….

IV. Importance du site pour l'enquêté

4.1. Pourriez-vous évaluer la part de vos revenus liée à l'exploitation de ce glissement de terrain ? ***Choisir une seule réponse***	1. 0 – 25% 2. 25 – 50% 3. 50 – 75% 4. 75 – 100%
4.2. Pourriez-vous évaluer la part de votre temps de travail consacrée à l'exploitation de ce glissement de terrain ? ***Choisir une seule réponse***	1. 0 – 25% 2. 25 – 50% 3. 50 – 75% 4. 75 – 100%
4.3. Pourriez-vous expliquer votre satisfaction à exploiter le glissement de terrain ?	1. Très satisfait 2. Satisfait 3. Moyennement satisfait 4. Moins satisfait 5. Nul
4.4. Dites pourquoi vous avez choisi cette échelle de satisfaction ? ***Question ouverte de contrôle que l'enquêteur pose***	1. Sols moins fertiles 2. Sol fertile 3. Coût de la location élevé 4. Location accessible 5. Fierté d'un terrain GT 6. Travail de sol difficile 7. Travail de sol facile 8. secheresse 9. alimentation familiale 10. vente des produits………

V. Plan d'aménagement de la parcelle

Dessin de l'exploitation et types de mise en valeur

VI. Identité de l'enquêté

6.1. Sexe de l'enquêté ***Ne pas poser la question***	1. Femme 2. Homme				
6.2. Quel est votre âge	1. 18-24 ans 2. 25-29 ans 3. 30-34 ans 4. 35-39 ans			5. 40-44 ans 6. 45-49 ans 7. 50 ans et + 8. Ne sait pas	
6.3. Quel est votre statut marital ?	1. Célibataire	2. Marié	3. Séparé	4. Veuf/ve	5. cohabitation
6.4. Niveau d'études	1. Primaire :	2. Secondaire :	3. Université :	4. Non scolarisé :	
6.5. Nombre d'enfants	1. Moins de 5 ans :	2. 5 – 12 ans :	3. 13 -18 ans :	4. Plus de 18 ans :	
6.6. Education des enfants	1. Primaire :	2. Secondaire :	3. Université :	4. Non scolarisé :	
6.7. Petits enfants en charge					
6.8. Quelles autres occupations avez-vous ? ***Choisir une seule proposition***	1. Enseignant 2. Commerçant 3. Administratif 4. Pécheur 5. Agriculteur 6. Chômeur 7. Autres………………….. (À préciser)				
Remerciements à adresser à l'enquêté pour le temps qu'il a accordé à répondre à nos questions et de la pertinence de ses réponses.					

Appendix C

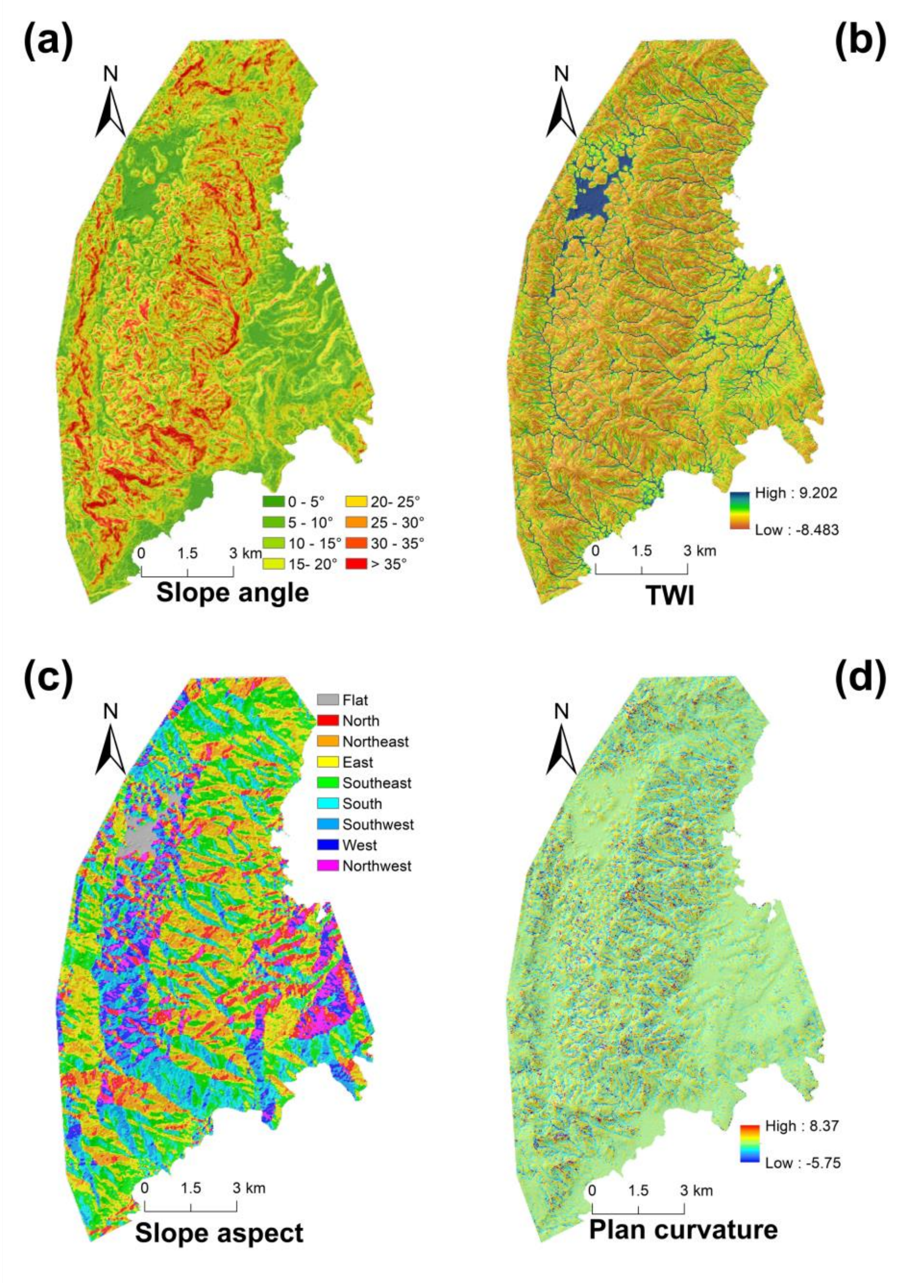

Figure C. 1: Additional predictors

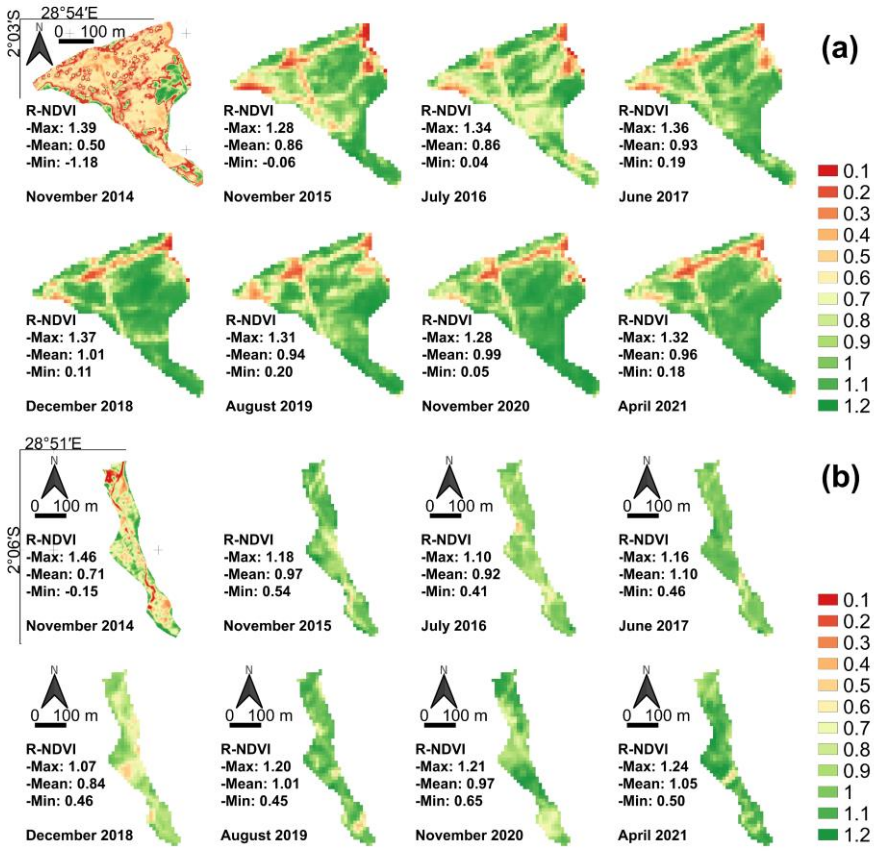

Figure C. 2: *Examples of rapid relative NDVI value changes for (a) deposit zone in Rambira (see Figure 4.2 b-f), zones with lower NDVI-relative are those in the talweg where debris from a recent deep-seated landslide is deposited (b) A section of the transport zone with rapid vegetation cover change*

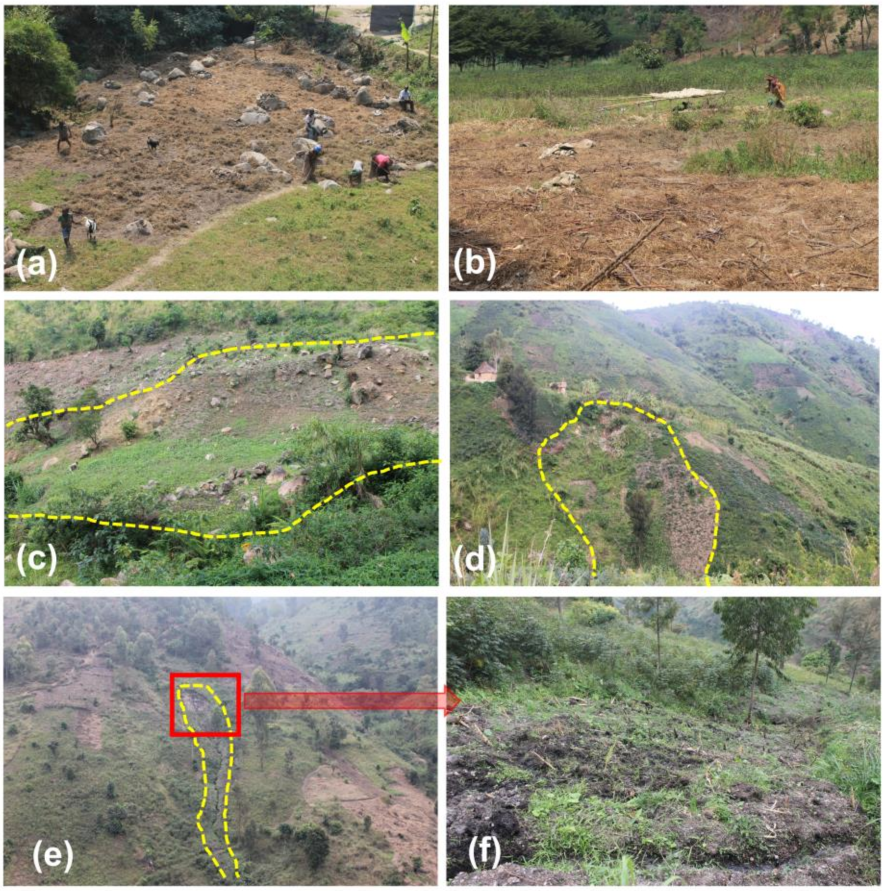

Figure C.3: Land uses for subsistence crops: in the deposit zone (a) tillage and (b) cassava cropping; (c) bean, maize, and cassava association crops in the transport zone; (d through f) crops association in the source zone.

Publications and conferences in context of the thesis

Publications in international peer-reviewed journals

Maki Mateso, J.-C, Bielders, C.L., Monsieurs, E., Depicker, A., Smets, B., Tambala, T., Bagalwa Mateso, L., Dewitte, O., 2023. Characteristics and causes of natural and human-induced landslides in a tropical mountainous region: the rift flank west of Lake Kivu (Democratic Republic of the Congo). Nat. Hazards Earth Syst. Sci. 23, 643–666. https://doi.org/10.5194/nhess-23-643-2023

Dewitte O, Dille A, Depicker A, Kubwimana D, **Maki Mateso J-C**, Mugaruka Bibentyo T, Uwihirwe J, Monsieurs E. 2021. Constraining landslide timing in a data-scarce context: from recent to very old processes in the tropical environment of the North Tanganyika-Kivu Rift region. Landslides 53: 23–45. DOI: 10.1007/s10346-020-01452-0

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A propos de l'auteur

Jean-Claude Maki Mateso est né à Bunia (RD Congo), le 23 mars 1981 où il a réalisé ses études de base de primaire et de secondaire. En secondaire, il a obtenu en 1999 un diplôme (Bac) d'Etat en section Biologie-Chimie à l'Institut d'Application de l'Institut Supérieur Pédagogique de Bunia. De ses études universitaires, il a réalisé, dans un premier temps, un graduat en Géographie et Sciences Naturelles (avec mention distinction au premier graduat) à l'Institut Supérieur Pédagogique de Bunia en 2003 ; puis, il a poursuivi avec une licence (Bac+5) en Géographie et Gestion de l'environnement à l'Université Pédagogique Nationale à Kinshasa (RD Congo) où il obtient en 2008 un diplôme de licence avec mention distinction. A l'année académique 2013-2014, il a réalisé, avec mention distinction, un master complémentaire en Gestion des risques naturels à l'Université de Liège (Belgique) à travers une bourse de l'Académie de recherche et d'enseignement supérieur (ARES). Collaborant depuis cette époque avec le Musée royal de l'Afrique centrale (MRAC, Tervuren, Belgique), notamment sur l'étude des glissements de terrain, il obtient en janvier 2018 une bourse de doctorat du Partenariat Sud du Conseil de l'Action Internationale (CAI) de l'Université catholique de Louvain (UCLouvain-Belgique). Ses recherches doctorales, à la croisée d'un partenariat UCLouvain – RMCA -CRSN Lwiro (ex-IRSAC, RD Congo), ont porté sur les interactions entre les glissements de terrain et les utilisations et la gestion des terres en se focalisant sur une zone d'étude sur les flancs du Rift à l'ouest du Lac Kivu (RD Congo). Un doctorat accompli au pôle de recherche « Earth and Life Institute - Environmental Sciences » de l'UCLouvain. Au cours de ses recherches doctorales sur le terrain, à travers les appuis des projets RESIST et HARISSA coordonnés par le MRAC en partenariat avec le CRSN Lwiro, il a été au contact d'acteurs locaux sur les questions des risques liés aux glissements de terrain. Sur sa carrière professionnelle, depuis 2011, il est chercheur au Laboratoire de géomorphologie et télédétection du Département de Géophysique au CRSN de Lwiro où il a débuté comme Assistant de recherche puis Attaché de recherche. Depuis 2014, il a aussi une expérience dans l'enseignement universitaire dans plusieurs universités du Sud-Kivu pour des cours abordant des thématiques liées à la géographie physique, la gestion de l'environnement et la télédétection-cartographie. Enfin, de manière plus générale, dans sa carrière de chercheur, Jean-Claude Maki Mateso s'intéresse à l'étude des changements environnementaux (naturels et humains) et de leurs impacts sur les aléas naturels dont ceux liés aux glissements de terrain en milieu tropical ; le tout dans une approche combinant de la géomorphologie et de la télédétection.