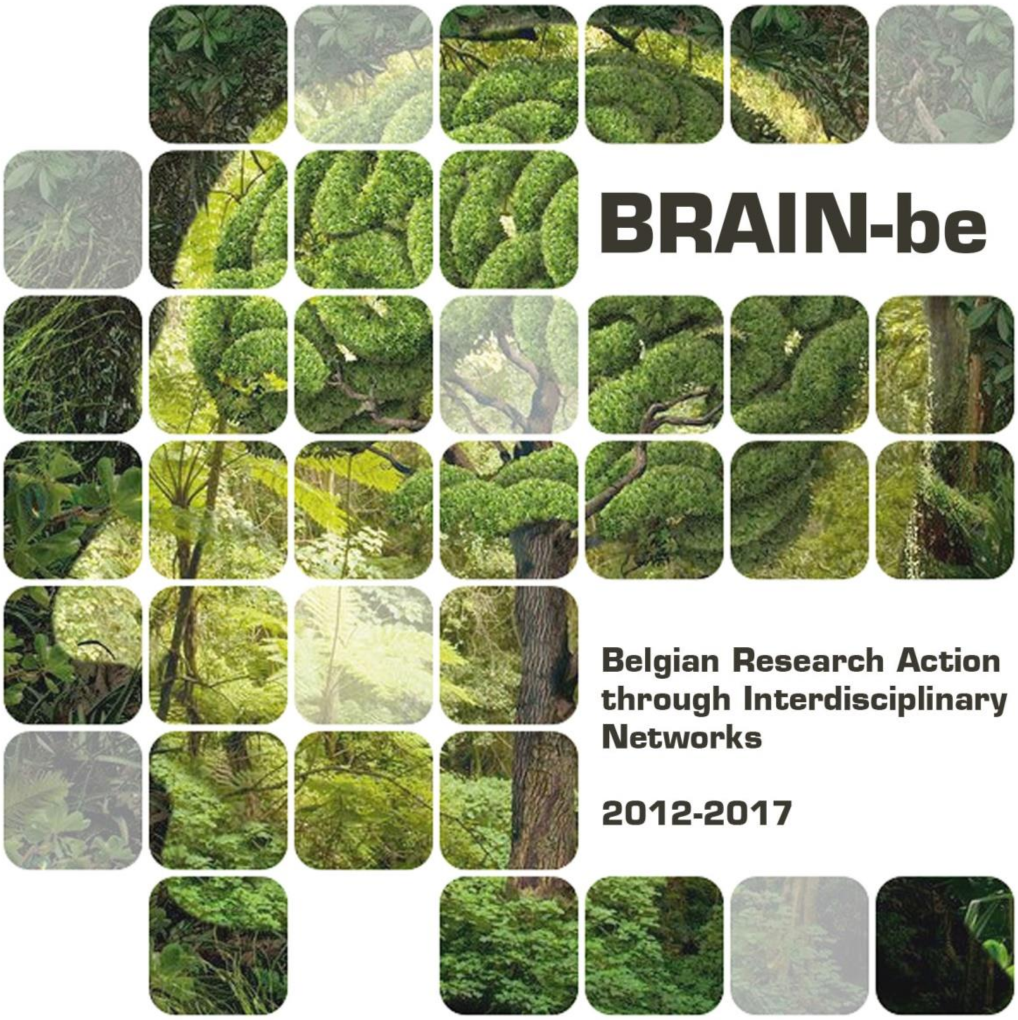

PAStECA

Historical aerial Photographs and ArchiveS to assess Environmental Changes in Central Africa

Olivier DEWITTE (RMCA) - Arthur DEPICKER (KU Leuven) - Nicholus ODHIAMBO MBOGA (ULB) - Benoît SMETS (RMCA) - Mohamed LAGHMOUCH (RMCA) - Caroline MICHELLIER (RMCA) - Axel DEIJNS (RMCA) - Thimm Zwiener (RMCA) – Taïs GRIPPA (ULB) - Liesbet JACOBS (KU Leuven) - François KERVYN (RMCA) - Moritz LENNERT (ULB) - Anton VAN ROMPAEY (KU Leuven) - Sabine VANHUYSSE (ULB) - Gerard GOVERS (KU Leuven) - Eléonore WOLFF (ULB)

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NETWORK PROJECT

PAStECA

Historical aerial Photographs and ArchiveS to assess Environmental Changes in Central Africa

Contract - BR/165/A3/PASTECA

FINAL REPORT

PROMOTORS: Olivier DEWITTE (Coordinator), Royal Museum for Central Africa (RMCA)
Gerard GOVERS, Katholieke Universiteit Leuven (KU Leuven)
Eléonore WOLFF, Université libre de Bruxelles (ULB) ...

AUTHORS: Arthur DEPICKER (KU Leuven) - Nicholus ODHIAMBO MBOGA (ULB) - Benoît SMETS (RMCA) - Mohamed LAGHMOUCH (RMCA) - Caroline MICHELLIER (RMCA) - Axel DEIJNS (RMCA) - Thimm Zwiener (RMCA) – Taïs GRIPPA (ULB) - Liesbet JACOBS (KU Leuven) - François KERVYN (RMCA) - Moritz LENNERT (ULB) - Anton VAN ROMPAEY (KU Leuven) - Sabine VANHUYSSE (ULB)

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WTCIII
Simon Bolivarlaan 30 Boulevard Simon Bolivar
B-1000 Brussels
Belgium
Tel: +32 (0)2 238 34 11 - Fax: +32 (0)2 230 59 12
http://www.belspo.be
http://www.belspo.be/brain-be

Contact person: XXXXXXXX
Tel: +32 (0)2 238 3X XX

Olivier Dewitte, Arthur Depicker, Nicholus Odhiambo Mboga, Benoît Smets, Caroline Michellier, Axel Deijns, Thimm Zwiener, Mohamed Laghmouch, Moritz Lennert, Liesbet Jacobs, François Kervyn, Anton Van Rompaey, Sabine Vanhuysse, Gerard Govers, Eléonore Wolff. ***Historical aerial Photographs and ArchiveS to assess Environmental Changes in Central Africa***. Final Report. Brussels : Belgian Science Policy Office 20XX – xx p. (BRAIN-be - (Belgian Research Action through Interdisciplinary Networks))

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ABSTRACT

Context: The conversion of natural lands into human-dominated landscapes is a major component of global environmental change. To quantify and understand the complexity of changes and subtle modifications in the environment, an accurate account of past landscape conditions has an important added value. However, sufficiently long, multidecadal records of landscape changes are almost inexistent for the least developed areas of the globe. **Objectives:** In PAStECA, we make use and valorise the Royal Museum for Central Africa (RMCA)'s unique collection of historical aerial photographs (and other archives) to reveal key information on the transformation of the environment from the mid of the 20th century and its impacts on geo-hydrological hazards and/or risks such as landslides, gully erosion and volcanic eruptions in the western branch of the East African Rift (Burundi, DR Congo, Rwanda). **Results:** First, we develop custom-made scanning and georeferencing protocols and tools of the photographs and produce digital orthomosaics. Then, machine learning models are developed to extract land use and land cover information from these georeferenced digital products. These photographs dating back to the 1950's are also used to quantify the impact of human activities on landslide rates. Covering over 60 years, we show that population dynamics, conflicts and deforestation affect geo-hydrological hazards and/or risks in both rural and urban contexts, with differences between the three countries. **Conclusion:** Through the production of new tools and models we evidence the need to preserve and valorise the aerial photographs and archives conserved at the RMCA to support present-day environmental change studies, especially in Central Africa.

Keywords: historical aerial photographs; land use and land cover change; natural hazard and risk assessment; population dynamics; Africa

1. INTRODUCTION

The general objective of the PAStECA project is to evidence the importance and the added value of archive documents to better understand present day issues in areas lacking baseline studies. In this project in particular, aerial photographs and archives conserved at the RMCA support present day environmental change studies in target tropical environments of Central Africa. The focus of the environmental topics relies on the spatio-temporal dynamics of the landscape and the associated Land Use and Land Cover (LULC) changes. The project deals with land occupation and demography, land degradation, hillslope processes and geo-hydrological hazard and risk issues.

The research area of the PAStECA proposal is the "geolocation for the valorisation of the historical, cultural and scientific heritage". This thematic priority of the Thematic Axis 3&6 calls for the interdisciplinary study of land use in the context of human-natural systems through the geolocation of the historical, cultural and scientific heritage. Aerial photographs are the best support that can be used for this purpose. Here the project makes use and valorise the RMCA's unique collection of historical aerial photographs over the entire DR Congo, Burundi and Rwanda that has the potential to reveal important information on the state of the environment in that region of Central Africa at the mid of the 20th century. Additionally to these photographs, archives such as relevant maps also available at RMCA (rural cadastre, urban cadastre, etc.) are used to provide supplementary information on historical LULC. These various collections are inventoried, digitized and georeferenced.

In this project we make the most of this heritage and the associated expertise through interdisciplinary research dealing with land use and land use change analysis; land degradation and Earth surface processes understanding; demography analysis, societal dynamics and risk assessment; cartography, GIS, remote sensing and photogrammetry techniques; database; collection management; and quantitative spatial modelling topics. We combine disciplines such as sociology, geography, geomorphology, geomatics, and demography.

The project also includes management of collection and its improvement with the aim of supporting its exploitation, particularly in a scientific way. Best practices of techniques and methodologies of sampling, digitizing and access to the information are also tested. The project not only manages existing digital data but also produces new digital products. The collection is clearly taking place upstream of the thematic research.

2. STATE OF THE ART AND OBJECTIVES

The conversion of natural lands into human-dominated landscapes is a major component of global environmental change (Turner et al., 2007). This conversion has been substantial during the past few centuries, but dramatically accelerated during the last decades (Lambin and Geist, 2006) and is expected to continue in the future (Lewis et al., 2015; Hurtt, et al. 2020). These human-induced transformations of environments can have impacts e. g. on biodiversity (Barnosky et al., 2011), climate and land surface feedbacks (Ostberg et al., 2015), soil degradation (Van Rompaey et al., 2002; Sidle et al., 2006) and ecosystem services (Montgomery, 2007; Luyssaert et al., 2014; Adhikari and Hartemink, 2016). Land use and land cover change (LULC), such as deforestation, construction of roads and mining activities, can also impact geo-hydrological hazards such as landslides, (flash)-floods and gully erosion ; increasing their frequency and/or intensity, and changing their spatial distribution (Vanacker et al., 2003; Bradshaw et al., 2007; Sidle and Bogaard, 2016; Tanyaş et al., 2022). Furthermore, unsustainable economic development, growing energy use, and uncontrolled and informal rapid urbanisation also contribute to increase risks (Merz et al., 2021; Raju et al., 2022).

In countries of the Global South, high population densities are common in urban and peri-urban regions as well as in the populated rural areas. These populations are often on the rise (exhibiting above-average growth patterns) and combined with high societal vulnerability (Seto et al., 2012; CRED – UNISDR 2018; Kii, 2021). As a result, uncontrolled and informal urbanisation commonly occurs (Bédécarrats et al., 2019), regardless of environmental constraints (Godschalk, , 2003; Tellman et al., 2021; Sapountzaki et al., 2022). The rapid growth of informal settlements, often located in areas unsuitable for construction, without basic services, consequently increases the vulnerability of large populations to natural hazards (IPCC, 2022; Ozturk et al., 2022). It is therefore not surprising that hazard risks are increasingly common threats for citizens in these regions of the Global South (Bradshaw et al., 2007; Froude and Petley, 2018; CRED UNDRR, 2020; Merz et al., 2021; Sapountzaki et al., 2022). In the future, changes in LULC, including deforestation, irrigation development and urban sprawl, will alter many drivers of geo-hydrological hazards and, as such, increase their impacts (Sidle et al., 2006; Bradshaw et al., 2007; Lewis et al., 2015; Jacobs et al., 2016; Rengers et al., 2016; Vanmaercke et al., 2016; Froude and Petley, 2018; Lacroix et al., 2020, Baumgartner et al., 2022). In addition, climate change has also the potential to alter the drivers of these hazards by increasing extreme weather events such as cyclones, storms, and floods (Seneviratne et al., 2012; Gariano and Guzzetti, 2016; Vanmaercke et al., 2016; Zscheischler and Seneviratne, 2017; AghaKouchak et al., 2020; IPCC, 2022). Despite these trends, geo-hydrological hazards and risks are still not properly documented and addressed, nor analyzed in a context-specific approach (Shroder and Papale, 2014; Maes et al., 2017; Vanmaercke et al., 2016; Guzzetti et al., 2020; Nkwunonwo et al., 2020; Dewitte et al., 2022). Yet, the need to better understand the past and current events in order to properly assess potential future occurrences and exposure is crucial (Simpson et al., 2021; Ozturk et al., 2022).

Assessing the processes of landscape transformation is of paramount importance if we are to embed sustainability in development strategies, ecosystem management, and land use planning, particularly for countries of the Global South where rates of LULC changes are highest (Verburg et al., 2013; Lewis et al., 2015). The complexity of these changes results from interactions and feedbacks across biophysical, socioeconomic, and governance factors occurring at different scales (DeFries et al., 2010; Meyfroidt et al., 2014) and it is increasingly explored and interpreted through the lens of coupled human-natural systems (Binder et al., 2013; Liu et al., 2015; Pelletier et al., 2015). However, quantifying landscape changes and their relation with current environmental issues remains a challenge, partly since the dynamics and trajectories of change are complex and fast-evolving and partly since robust methods for analyses are still in development for many LULC processes (Pelletier et al., 2015).

To quantify and understand the complexity of changes and subtle modifications in the environment, an accurate account of past landscape conditions and recent changes over a multidecadal time scale has an important added value. Indeed, the documentation of long-term trajectories of LULC change can yield important new insights because (i) the importance of some of the drivers of LULC change, such as demographic growth and rural-urban migration, only becomes apparent over sufficiently long-time spans and (ii) the relative importance of drivers of LULC change changes significantly over such time scales. However, sufficiently long, multidecadal records of landscape changes are almost inexistent for the least developed areas of the globe. This important lack is not easy to fill: global and regional LULC assessments derived from the first satellite data from the 70s and 80s offer a spatial resolution that is often too coarse for this purpose (Joshi et al., 2016) and the very high resolution satellite data became available only at the end of the 90s at best (Joshi et al., 2016; Belward and Skøien, 2015). The use of historical black and white aerial photographs offers the possibility of studying a longer time frame. Such photos show excellent spatial details that make them appropriate for studying, for instance, topics as different as forest transition (Belay et al., 2015), landslide dynamics (Dewitte et al., 2009; Lopez-Saez et al., 2016), soil erosion (Molina et al., 2012; Makanzu Imwangana et al., 2014) and urban sprawl (Molina et al., 2012; Makanzu Imwangana et al., 2014).

Although this added value of historical aerial photographs is evident, especially in Africa where data availability is scarce, their use is still too often limited by quality or availability of ancillary data. The unique collection of historical aerial photographs (> 300,000 photographs) that are conserved at the RMCA and that cover the entire DR Congo, Burundi and Rwanda have the potential to fill this gap. These are an important but hitherto poorly exploited archive from the mid of the 20th century. Additionally to these photographs, archives such as relevant maps also available at RMCA can provide supplementary information on historical LULC.

The general objective of the PAStECA project is to make use and valorise the aerial photographs and archives conserved at the RMCA to reveal key information on the transformation of the environment and its impacts on geo-hydrological hazards and/or risks such as landslides, gully erosion and volcanic eruptions in target tropical environments of Central Africa. The first specific objective is to produce georeferenced digital products of the historical photographs and archives that can be used for LULC studies in general. The second specific objective of this proposal is to explore the causes, impacts, scales and trends of the LULC and its changes in the context of geo-hydrological hazards and risks with the help of these digital products. The third specific objective is dedicated to improve accessibility of digital products related to historical photographs, archives and LULC changes to foster their exploitation.

3. METHODOLOGY

The project deals with land occupation and demography, land degradation, geomorphology, geo-hydrological hazards and risks, and geomatics.

Selection and understanding of the study area – a key for the achievement of the project

The analysis of the landscape and the spatio-temporal dynamics of LULC to understand current environmental changes through the valorisation of historical aerial photos and archives requires the combination of different disciplines. It also requires to target on key areas as the complete collection of the aerial photographs of RMCA covers a large territory of Central Africa and is far too large and beyond the scope of a single, four-year project that aims to thoroughly investigate the impact of interactions and feedbacks across biophysical, socioeconomic, and governance factors on the landscape and its LULC.

In order to carry out the project in the most efficient way, research is focussed on a well-defined study area located in the tropical mountainous environments of the western branch of the East African Rift (Figure. 1). The region of interest extents from the North Tanganyika rift zone in the south to the Virunga Volcanic Province in the north. Its landscape and LULC evolution is very interesting to study because of the combination of the following natural and human characteristics:

- The area has one of the highest population densities of Africa, urban expansion is very fast and anthropogenic pressure high. For example; in the DR Congo, the average density of the wider Kivu region was estimated to 17 inhabitants per km² in 1958 (Meditz and Merrill, 1994) while in 2000 the density was already 192 inhabitants per km² (https://data.jrc.ec.europa.eu/dataset/jrc-ghsl-ghs_pop_gpw4_globe_r2015a). In

Rwanda the current population density is > 500 inhabitants per km² (https://population.un.org/wpp/). Bukavu, Bujumbura and Goma are cities with population ~800,000 each (a few thousands during the colonial period) (Michellier et al., 2016). That population increase has a drastic effect in urban areas but also in rural areas where land conflicts are a real issue (Butsic et al., 2015; Ordway, 2015);

- A large majority of the population relies on agricultures; a significant part of the population is directly or indirectly related to mining sector and both are contributing to land degradation;
- The area is at the border between three countries, namely Burundi, DR Congo and Rwanda (with different governance policies and socioeconomic characteristics);
- A tropical environment with uncontrolled urbanization and deforestation (Seto et al., 2012; Hansen et al., 2013; Figure 2);
- Landscape is diverse (mountains, lakes, rivers, volcanoes, pristine forest, highly human-transformed landscapes) and soil and climate are very favourable for agriculture expansion;
- The area is affected by years of conflicts that in turn are jeopardizing the socio-economic development and impacting LULC (migration, land pressure on protected areas, mine control);
- A global hotspot of geo-hydrological hazards (Broeckx et al., 2018; Emberson et al., 2020). Natural triggering and predisposing factors such as heavy rainfall, tectonic activity and steep topography favour the occurrence of landslides and soil erosion processes (included large gullying) (Jacobs et al., 2016) (Figure 3 and Figure 4). In addition, Nyamulagira and Nyiragongo are two very active volcanoes, source of various hazards (lava flow, toxic gas release) (Smets et al., 2010; Smets et al., 2015; Smittarello et al., 2022). The volcanic risk and the lava flows in particular are adding more pressure on land use planning in the region of Goma;
- RMCA has developed a unique long-term expertise in the region over the last decade and has collected unprecedented datasets for similar environments;
- MRAC and ULB have developed a large network involving local institutions and the civil society in the framework of the GeoRisCA project.

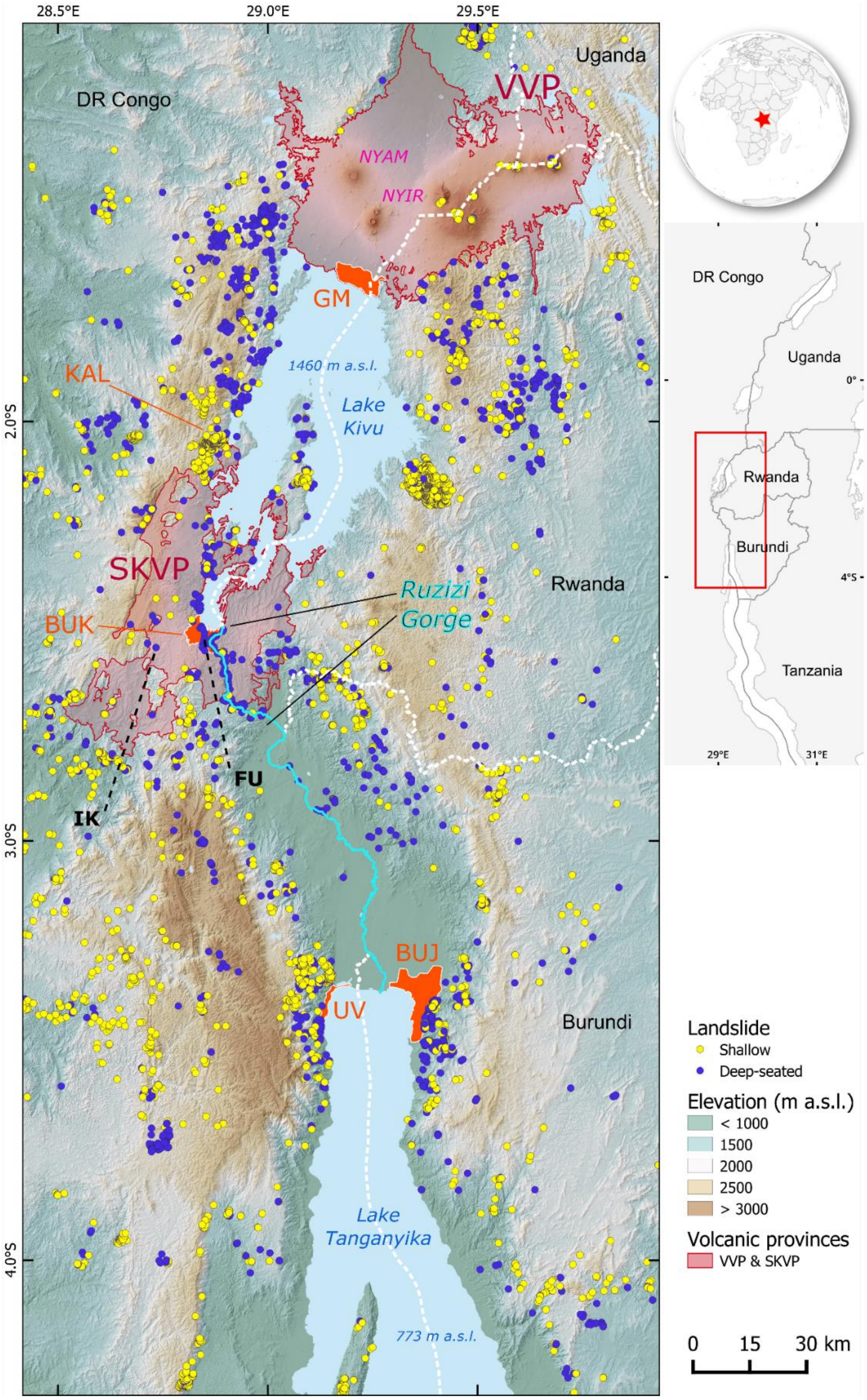


Figure 1. Study area of PAStECA project. The main natural physical features of the landscape are presented together with the main city centres. Location of > 8,000 landslides largely identified through the PAStECA projects (Depicker et al., 2020; Dewitte et al., 2021) is represented in red. VPP, Virunga Volcanic Province. SKVP, South Kivu Volcanic Province. NYAM, Nyamulagira volcano. NYIR, Nyiragongo volcano. BUJ, Bujumbura. BUK, Bukavu. GM, Goma. KAL, Kalehe. UV, Uvira. IK, Ikoma landslide. FU, Funu landslide. Figure from Dewitte et al. (2021, manuscript in supplementary material)

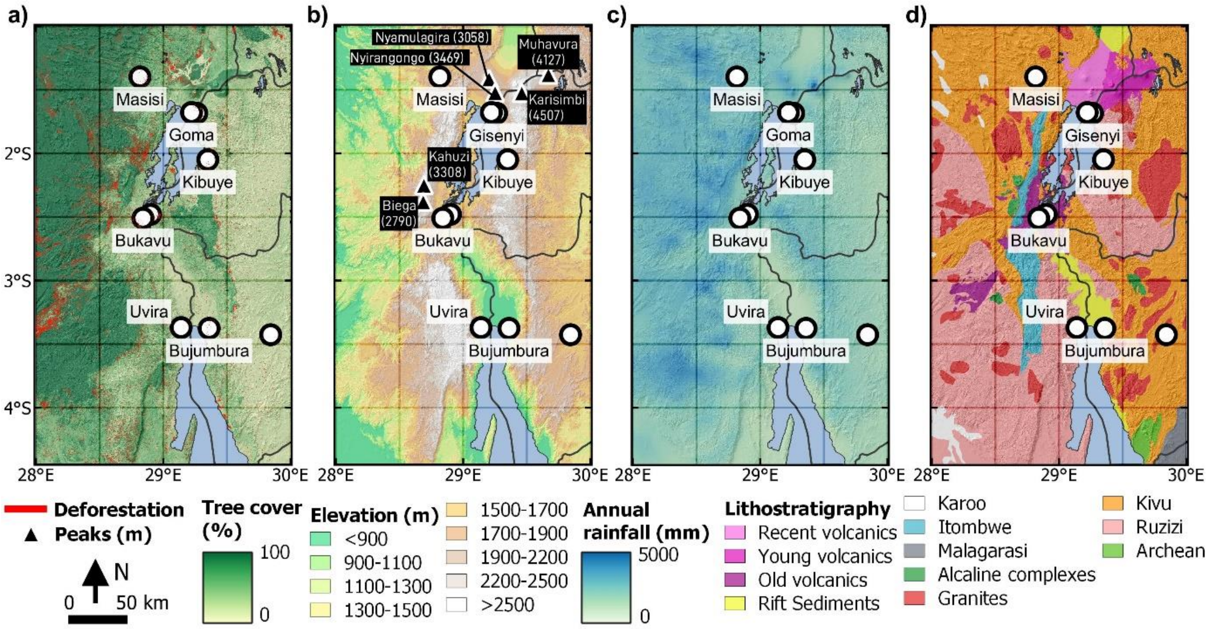


Figure 2. Environmental characterization of the study area of the PAStECA project. (a) tree cover for the year 2000 and deforestation from 2001–2017 (Hansen et al., 2013), (b) elevation and some renowned mountain peaks (height expressed in meters) (USGS, 2006), (c) average annual rainfall between 2005–2015 (Van de Walle et al., 2020); (d) lithostratigraphy (Table I) (Laghmouch et al., 2018a). Figure from Depicker et al. (2021a, manuscript in supplementary material).

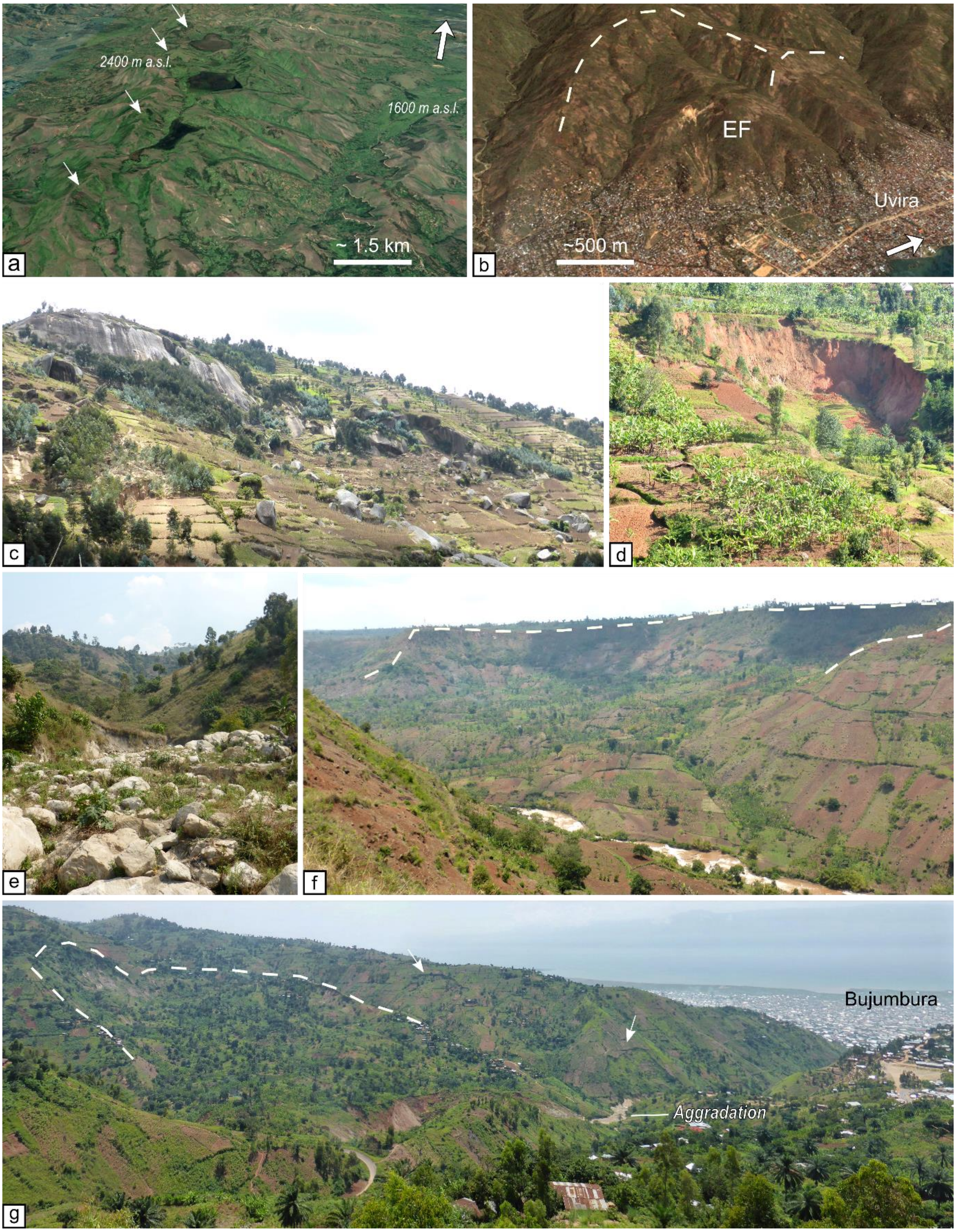


Figure 3. Landslides of natural origin. a. Google Earth image of a mountain slope deformation (~ 40 km2) in DR Congo, south of Bukavu. White arrows indicate the main scarp (− 2.703°, 28.809°). b. Google Earth image of slides along a fault system in Uvira (DR Congo). EF denotes an active earthflow on a displaced block (− 3.391°, 29.127°). c. Rock fall/avalanche in a granite outcrop in Rwanda, Sept. 2018 (− 1.666°, 28.561°). d. Recent rotational slide developed in thick regolith in Rwanda, Sept. 2018 (− 1.804°, 29.606°). e. Debris flow triggered by an intense thunderstorm on 25 Oct. 2014 in Kalehe (DR Congo). Photo taken in July 2015 attests the quick vegetation regeneration (− 2.044°, 28.899°). f.

Rotational slide along the Ruzizi Gorge. Photo taken from DR Congo (Oct. 2017), Rwanda is in the background (− 2.637°, 28.909°). g. Active slide—earthflow (Bujumbura, February 2015). White arrows indicate the main scarp of smaller landslides (− 3.431°, 29.387°). The terminology of the landslide processes is based on Hungr et al. (2014) and will be the terminology used throughout the report. Several of the landslides shown in this figure have been observed during PAStECA field missions. The figure is from Dewite et al. (2021, manuscript in supplementary material).

Figure 4. Landslides caused by human disturbances. a Landslides developed along a large gully system in Bujumbura, Feb. 2015 (− 3.409°, 29.381°). b Deep-seated (flow) slide in Rwanda (Sept. 2018) developed on a terraced hillslope carved in regolith (− 2.049°, 29.460°). c Mining (Coltan) triggers gullying, which triggers landslides, Rwanda, Sept. 2018 (− 1.987°, 29.604°). d Flowslide in regolith affecting a gold mining site in South Kivu, DR Congo, June 2016 (− 2.857°, 28.736°). e River incision in colluvium/alluvium in Bujumbura (Sept. 2013) and subsequent bank erosion and landsliding (− 3.399°, 29.383°). f Rock avalanche at a road cut in Rwanda, Sept. 2018 (− 1.825°, 29.627°). The terminology of the landslide processes is based on Hungr et al. (2014) and will be the terminology used

throughout the report. Several of the landslides shown in this figure have been observed during PAStECA field missions. The figure is from Dewitte et al. (2021, manuscript in supplementary material).

The need to reply to challenging research questions

For the region of interest, most questions related to LULC and the changing environments remained unclear and research outputs will be directly relevant to society. For instance, many new landslides occur every year in the region and some of them have dramatic impacts (fatalities, damages to the infrastructures, etc.). From a local perspective, local research partners and stakeholders mention an increase in the frequency of these events and invoke climate change and/or direct human-induced environmental change (deforestation, urbanisation) as main causes. None of these statements had been accurately checked when PAStECA was initiated. The causal relationship between landslide processes, climate change and land use change therefore remained hypothetical and the more frequent reporting may simply be related to the increase in population density in the area. The challenge here was to see how these LULC changes already impacted and/or will likely affect earth surface processes and hazards, which, in turn, may have impacts on humans (economic activities such as peri-urban agriculture, infrastructures management such as road network, water pipes, urban planning,…). The fundamental challenge was to gain insight in what might be called the baseline rates/frequencies of these processes, i.e. the rates/patterns that would occur under natural conditions whereby geophysical, biophysical, and climatic conditions control temporal and spatial variations as well as the way in which humans have affected these processes, so that more effective remediation strategies can be laid out.

Project structure – work packages

To answer these questions, the PAStECA is organized around nine scientific Work Packages (WP) (Figure. 5). There are three transversal WPs: WP 1 provides the basic data that are the cornerstone of the project, WP 8 integrates, through different modelling approaches, the outputs from the other WPs, and WP9 concerns the dissemination on the web of the georeferenced historical data and the produced maps in order to share data with the scientific community at large and also raise awareness of the importance of land use change to the general public, policy makers and land managers.

The other WPs are organised into two related groups, the first focusing on the production of a georeferenced digital collection directly from the historical data available at MRAC and the production of derived digital LULC products. The second group concerns the analysis of the changing environment. It involves several WPs that are strongly interconnected. The project goes across disciplines such as population science, geography, geomorphology, geomatics and remote sensing.

Each WP has its own methodological challenges and relies on specific methods. In each case the methods used are based upon well-established techniques supplemented with more novel approaches.

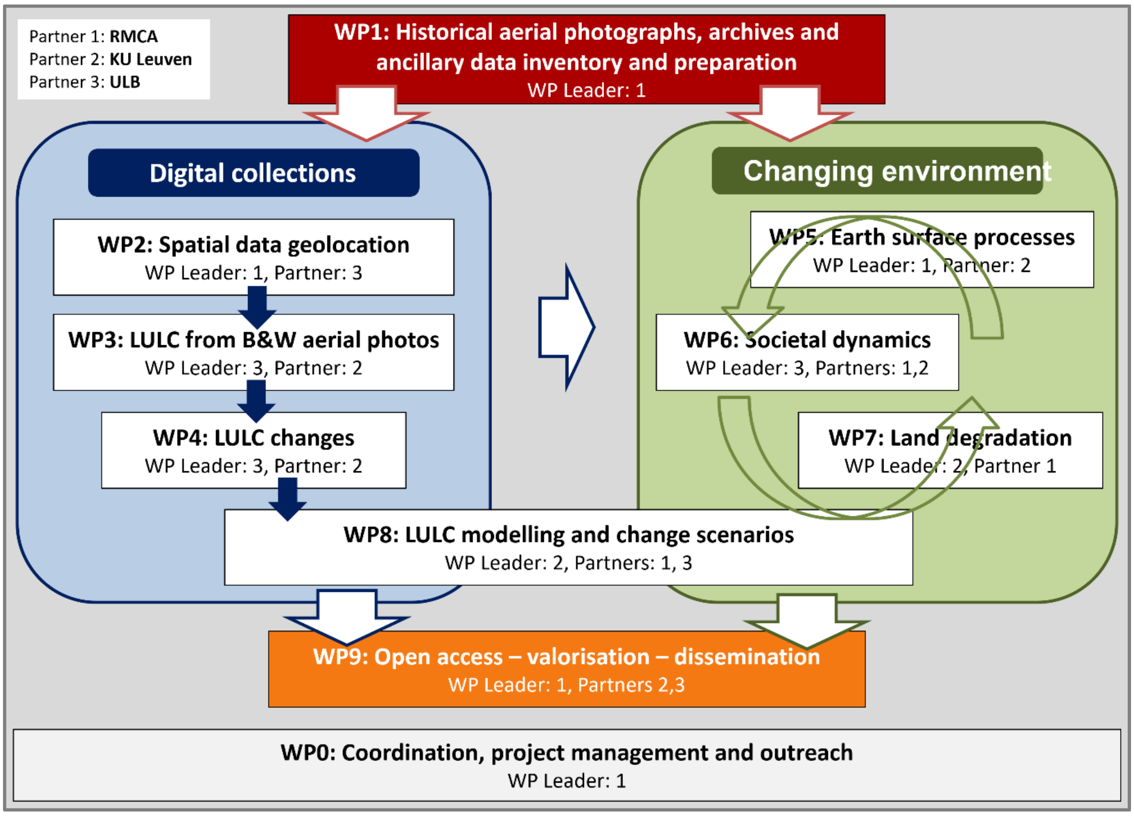


Figure 5. Structure of the PAStECA project.

Balancing the tasks - targeting places of interest – scale of investigation

Scanning, georeferencing and photogrammetric processing (WP 2 and 3) are time consuming tasks but essential for the unlocking of the archive. Another time-consuming but key task is the visual analysis of the aerial photographs in stereoscopy. This approach is the only way to identify and map correctly earth surface processes such as landslides, soil erosion features and river dynamics (WP 5) and to analyse in detail the related land degradation and associated hazards (WP 7). It also assists in visual LULC interpretation (WP3). LULC interpretation and risk trend analysis also require a lot of information from local stakeholders for example. To ensure that a balanced time between the tasks was kept and that in any case we have good material for research, the project worked at two scale levels:

- Three urban areas of Goma in DR Congo (+ the connected city of Gisenyi in Rwanda), Bukavu in DR Congo, Bujumbura in Burundi, and their hinterland (Figure 1. and Figure 6). Goma, Gisenyi and Bukavu are found on the northern and the southern shores of Lake Kivu, respectively. Bukavu is characterized by hilly terrain, whereas Goma and Gisenyi are built on the flat lava field of the Nyiragongo and Nyamulagira volcanoes. Bujumbura lies on the northeastern coast of Lake Tanganyika, extending over a flat plain which turns into steep slopes on its eastern outskirts. Bukavu and Bujumbura are exposed to regular landslide, flood and gully erosion hazards (Nibigira et al., 2018; Nobile et al., 2018) whereas Goma and Gisenyi are exposed to volcanic hazards (Chirico et al., 2009; Poppe et al., 2016; Smets et al., 2017, 2010). All three cities are exposed to seismic hazards (Delvaux et al., 2017; Smets et al., 2016). High population densities of greater than 300 inhabitants per km2 and rapid urbanization associated with a high social and economic vulnerability prevail in the area (Michellier, 2017; Michellier et al., 2016). With these three target places, we cover the main natural and human issues we aim to study (**Figure 7**). These places also concentrate the areas for which the availability of ancillary data (produced mostly by RMCA) was the highest (Figure 8).

- Regional level: this focus concerns the deforestation and the landslide related issues.
- In addition to the local focus of the three urban areas, two rural areas (Kalehe and Rusizi River) were also analyzed. For these two rural focuses, the analyses relied directly on PAStECA digital outputs, but were partly carried out with the support of other project fundings.

Figure 6. Panoramic view of Goma at the foot of Nyiragongo volcano (in the background), (B) Panoramic view of over the large Funu landslide of Bukavu and in (C) Panoramic view of Bujumbura, from the rift slope towards Lake Tanganyika. Figure from Mboga at al. (in review, manuscript in supplementary material).

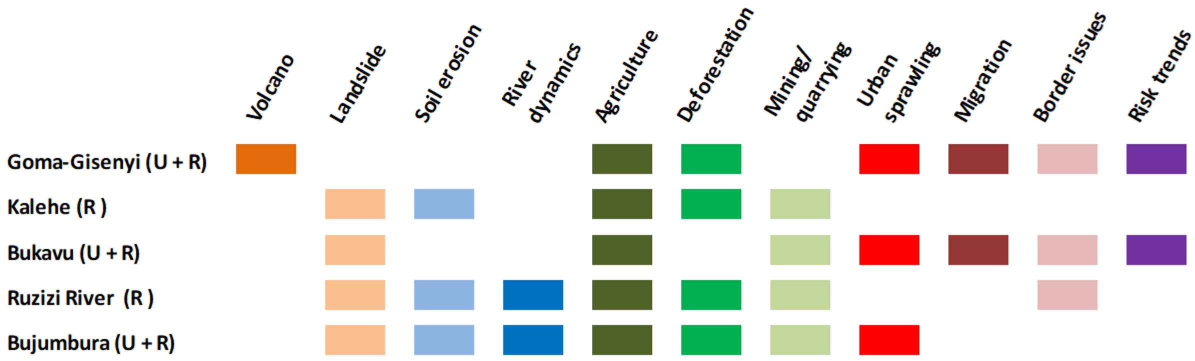


Figure 7. Main biophysical and societal issues for the five target places. Bujumbura is in Burundi; Bukavu and Kalehe in DR Congo, Ruzizi River is at the border between DR Congo and Rwanda. Goma is in DR Congo; Gisenyi is contiguous with Goma, the city across the border in Rwanda. A balance between Urban (U) and Rural (R) environments is ensured.

Data available at the start of the PAStECA project

This project relied on both historical colonial period and post-colonial data. The list of the main data used in PAStECA is shown in Fig. 8a. Black and white historical aerial photographs (Figure 8b) and historical archives are the key data of the project. They are all from RMCA's collections. Other data were produced or acquired via RMCA research projects.

The ~12,000 historical photographs for the region of interest were taken at scales ~1:20,000 to ~1:40,000 and sometimes have a poor quality. In the 70s and 80s, the National Geographic Institutes (NGIs) of France and Belgium contributed to the surveying and mapping of Burundi and Rwanda; these photographs are conserved in paper format (copies from the originals) at RMCA. In Burundi a new aerial photo coverage was acquired too in 2014 that is archived at the Bureau Central de Géomatique (available there on demand). RMCA has acquired the digital orthoimage produced from those 2014 photographs. For the five target places, Very High Resolution (VHR) satellite images (Pléiades, 0.5 m resolution) are available and orthorectified for 2013 and 2015. For Bukavu, Ruzizi River and Bujumbura, tri-stereo Pléiades Digital Elevation Models (DEM) were computed at 1.0 m resolution. A 5 m DEM has been computed from RADAR data for the region in DR Congo stretching from Bukavu to the Virunga (Albino et al., 2015).

Archives from both colonial and post-colonial times consist mostly in cadastral maps, landscape sketches, notes from colonial field works and population census. The data presented in Figure 8a in the categories "natural environment" and "society" are all in digital format and are linked to comprehensive digital databases. These data are of various spatial resolutions. Lava flow maps, administrative maps and population data (2016) are at a very high resolution and accuracy; they were collected through other RMCA projects.

A

	Year	Goma-Gisenyi	Bukavu	Kalehe	Ruzizi River	Bujumbura	Origin
Aerial Photographs	1950s - 1960	S	S	S	S	S	C
	1970s	S	S	S	S	S	C
	1980s		S		S	S	O
	2010s						
Archives	before 1960						C
	after 1960						C
Recent field notes and photos	2010s -2016	D	D	D	D	D	C
Satellite images							
Very high resolution (1,2)	2010s	D	D	D	D	D	R
High-medium resolution (1,2,3)	2010s	D	D		D	D	R
Low-medium resolution	1980 -2000s	D	D	D	D	D	O
Orthophotos	2014					D	O
Topography (DEM)							
1 m resolution (2)	2013		D		D	D	
5 m resolution (4)	2015	D	D	D	D		R
10 m resolution	2011					D	O
Natural environemt							
Landslide inventory (1,2)	2016		D	D	D	D	R
Landslide prediction maps (1,2)	2016	D	D	D	D	D	R
Soil map (5)	2016	D	D		D	D	R
Seimicity maps (1)	2016	D	D	D	D	D	R
Lava flow maps (1,3)	2016	D					R
Society							
Health maps (6)	2016					D	R
Administrative maps (1,7)	2014	D	D		D	D	R
Population data (1)	2016	D	D				R

D = in digital format at RMCA; **C** = RMCA collection; **R** = RMCA research outputs ; **O** = other origin

1 = GEORISCA (BELSPO-SDD, 2012-2016); 2 = RESIST (BELSPO-STEREOIII, 2014-2019); 3 = GORISK (BELSPO-STEREOII, 2007-2010); 4 = VI-X (BELSPO-STEREOII, 2012-2014); 5 = Carte pédologique du Burundi (BTC Project); 6 = Carte Sanitaire du Burundi (BTC Project); 7 = DRC provinces (DGD Project)

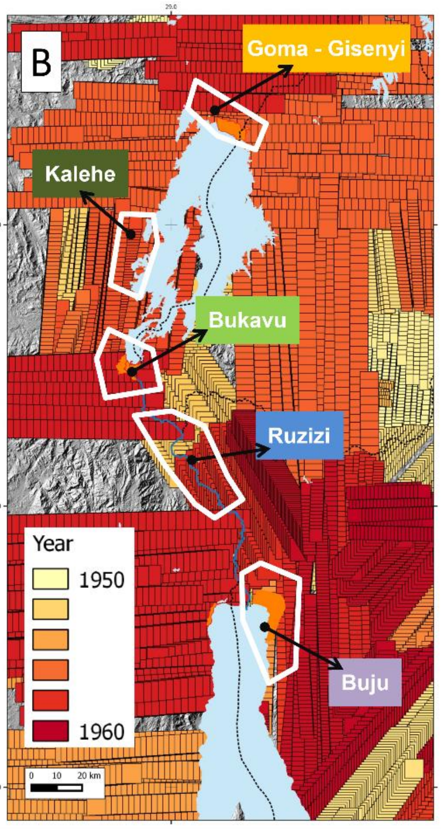


Figure 8. Main data used in PAStECA. (A) Availability is presented for the five target places, Figure 7). Historical data are in red. Data already available in digital format at RMCA are symbolized "D". Symbol "S" is for analogical datasets partly scanned. Symbol "C" is used to stress they come from RMCA's collections; "R" means research outputs form recent RMCA projects (numbered 1 to 7). Symbol "O" is for data from other origins but also available at RMCA. (B) Spatio-temporal distribution of the ~12,000 B&W historical aerial photographs that cover the region presented in Figure 1. The five target places are indicated on the map. Most of the photos are already scanned for those places . Light-yellow to dark-red photos correspond to dates from early 1950 to 1960. The map visualises the most recent historical photographs. In many places, several covers are available for the period 1950-60.

Complementarity and synergies

PAStECA represented a significant complement to and benefited from several other initiatives funded in the region. When the PAStECA project was designed and submitted, three BELSPO supported projects were in operation: GeoRisCA (SSD Programme, 2012-2016, RMCA is PI), RESIST (STEREO III Programme, 2015-2018, RMCA is PI) and AfReSlide (BRAIN-be Programme, 2013-2018, RMCA is partner) projects. PAStECA project was also complementary to the GEOKIVU project (supported by DGD, 2016-2019, RMCA is PI). These projects were all contributing to a better understanding of environmental changes in the studied region, to the valorisation of archives, and to the development of a, at that time, more than 10-years-long Belgian expertise. PAStECA was framed around the outputs of these projects but was aimed to provide novel complementary insights by explicitly focusing on a longer time scale and by using hitherto unexploited resource.

Before we elaborate more on the achieved work, it is important to mention that between the project submission (Sept. 2016) and its actual start 1st of October 2017, new research initiatives (highlighted with a *) with RMCA as PI or partner took place in the PAStECA study area (see also Section 6 for the thesis description). In year two (HARISSA) and year 3 (GuiDANCE) another two projects took place. Several BSc, MSc and internship projects have provided extra inputs. These activities supported several WPs and covered the five target places (Figure 8). These new research initiatives are listed here:

- *A 2017 helicopter-based very high-resolution (VHR) imaging of the target region of Goma (support to WP2 and 3). RMCA is PI. Status: achieved;
- *A 4-year PhD thesis (Thesis 1) on landslide dynamics and ground deformation in the Bukavu target region (support to WP 2, 5 and 7). RMCA is PI. Status: achieved;
- *A 4-year PhD thesis (Thesis 2) on landslide and soil conservation in the Kalehe target place (support to WP4, 5, 6, 7). RMCA is co-PI. North-South collaboration. Status: in progress;
- *A MSc thesis (Thesis 3) on landslide and environment changes in the target region of the Ruzizi river (support to WP4, 5 and 7). RMCA is PI. North-South collaboration. Status: achieved;
- *A 3-year PhD thesis (Thesis 4) on landslide characterization in the Bujumbura target region (support to WP 5and 7). RMCA is co-PI. North-South collaboration. Status: achieved;
- **A MSc thesis (Thesis 6) on the history of ground deformations in the target region of Bujumbura (support to WP2, 3, 4, 5 and 7). RMCA is PI, ULB partner. Status: achieved;
- **A 5-year project supported by the Belgian Development Cooperation (DGD) on Natural HAzards, RISks and Society in Africa (project HARISSA). This project aims at developing knowledge and capacities in the PAStECA region. RMCA is PI. North-South collaboration with local stakeholders. Status: in progress;
- **A 5-year project (project GuiDANCE) supported by BELSPO (FED-tWIN) that supports a senior research position on remote sensing of geohazards in African urban regions, with a focus on the use of the historical photographs support to WP1 and 2). RMCA is PI. Status: in progress.
- ** Two MSc thesis (Thesis 9 and 10) on landslides and environmental changes in Rwanda (support to WP4, 5 and 7). KU Leuven is PI, RMCA is partner. Status: achieved.

4. SCIENTIFIC RESULTS

4.1. Archive data, preparation and geolocation (WP1 & WP2)

Aerial photographs

Aerial photographs, archives and other ancillary data that are needed for the project (and hopefully for further analysis) were inventoried. The scanning and archiving in digital format of all aerial photographs, flight plans and maps corresponding to the geographic zone targeted by PAStECA are listed in (Table I). The scanned photos are shown in Figure 9. An example of a flight plan indicating the location of the photographs is shown in Figure 10.

Table I. List of aerial photographs datasets inventoried and scanned for PAStECA. Total number of inventoried aerial photographs: 8947 photos. Total number of scanned aerial photographs: 8947 photos.

Geogr. Zone	Dataset	Year (rounded)	Nbr of photos	Status
North Kivu	Lubero-Rutshuru	1959	911	SCANNED
North Kivu	Lacs Mokoto-Masisi	1950		**MISSING**
North Kivu	Volcans (sud Rutshuru)	1956-1957	155	SCANNED
North Kivu	Virunga Volcans	1958	97	SCANNED
North Kivu	Kisenyi-Goma	1947	17	SCANNED
North Kivu	Goma-aérodrome	1952	33	SCANNED
North Kivu	C.U. Goma	1955	22	SCANNED
North Kivu	Baie de Sake	1950	20	SCANNED
North Kivu	Walikale-Rutshuru	1958	337	SCANNED
South Kivu	Kasha-Bukavu	1954	20	SCANNED
South Kivu	Shangugu	1954	36	SCANNED
South Kivu	Bukavu-Kalehe	1954-1959	556	SCANNED
South Kivu	Bukavu	1959	209	SCANNED
South Kivu	Bloc Bukavu	1960	97	SCANNED
South Kivu	Haute Rusizi	1955	493	SCANNED
South Kivu	Nord Rusizi	1959	289	SCANNED
South Kivu	Basse Rusizi	1958	87	SCANNED
South Kivu	Itula-Mwenga-Uvira	1956-1959	1674	SCANNED
Rwanda	Kibuye-Kisenyi-Kigali	1958	1640	SCANNED
Rwanda	Rwanda 1974	1974	868	SCANNED
Burundi	Usumbura	1955	88	SCANNED
Burundi	Usumbura-Bururi	1958-1959	203	SCANNED
Burundi	Burundi 1973	1973	792	SCANNED
Burundi	Burundi TROU	1974	162	SCANNED
Burundi	Burundi 1981-82	1981-1982	141	SCANNED

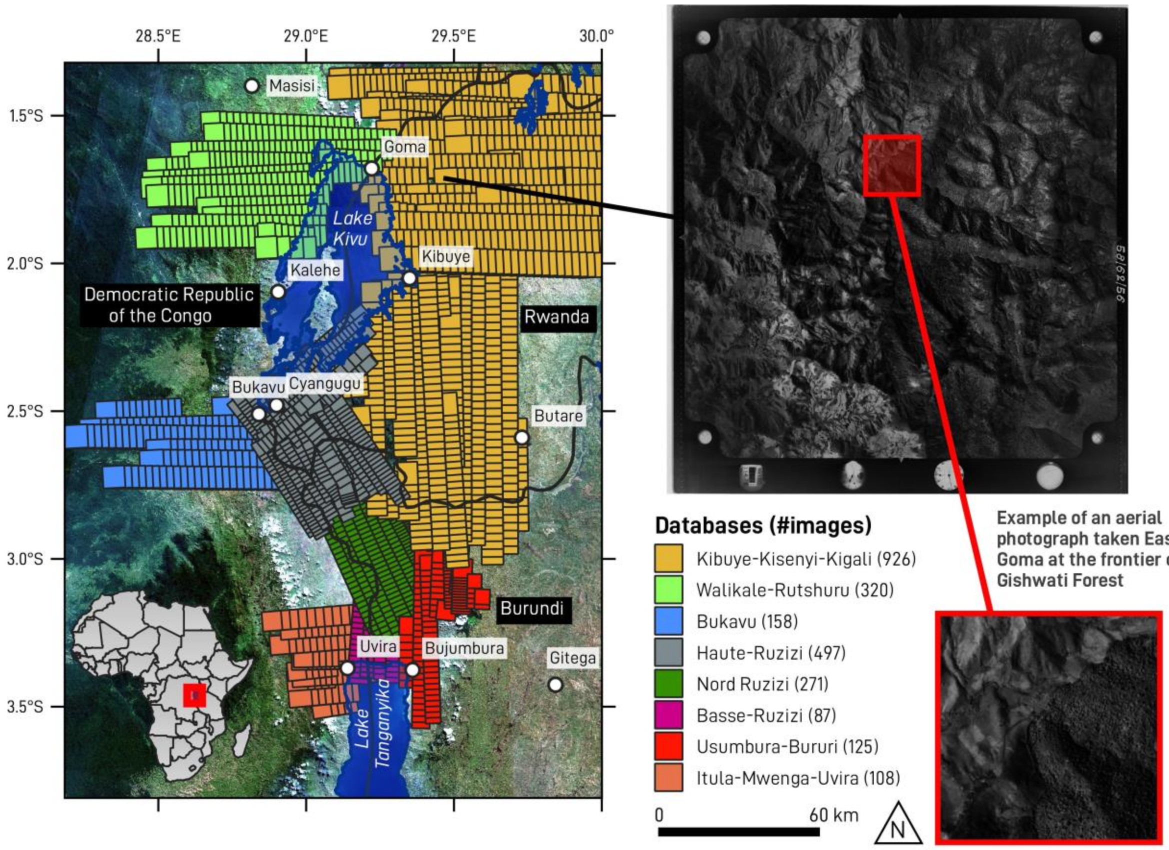
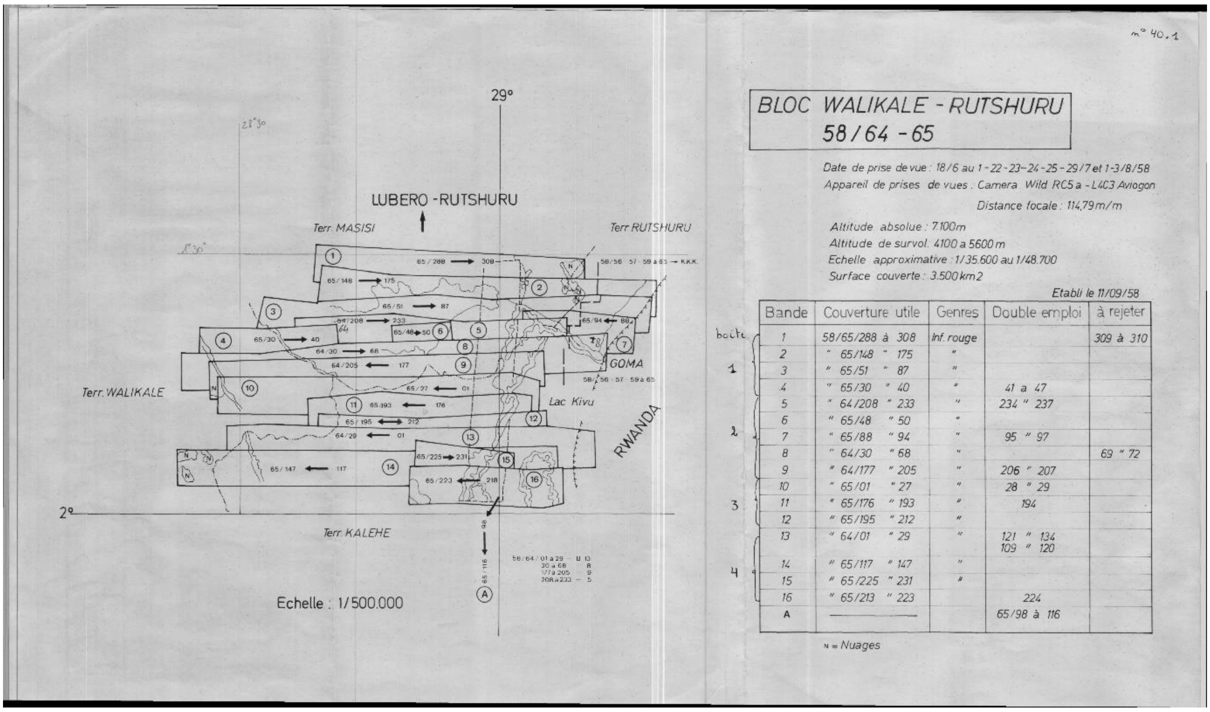


Figure 9. Map of the PAStECA's region of interest, with the footprint of the scanned photographs and produced orthomosaics.



n° 40.1

BLOC WALIKALE - RUTSHURU
58 / 64 - 65

Date de prise de vue : 18/6 au 1-22-23-24-25-29/7 et 1-3/8/58
Appareil de prises de vues : Camera Wild RC5 a - L4C3 Aviogon
Distance focale : 114,79m/m

Altitude absolue : 7.100m
Altitude de survol. 4100 a 5600 m
Echelle approximative : 1/35.600 au 1/48.700
Surface couverte : 3.500 km2

Etabli le 11/09/58

boîte	Bande	Couverture utile	Genres	Double emploi	à rejeter
1	1	58/65/288 à 308	Inf. rouge		309 à 310
	2	" 65/148 " 175	"		
	3	" 65/51 " 87	"		
	4	" 65/30 " 40	"	41 a 47	
2	5	" 64/208 " 233	"	234 " 237	
	6	" 65/48 " 50	"		
	7	" 65/88 " 94	"	95 " 97	
	8	" 64/30 " 68	"		69 " 72
	9	" 64/177 " 205	"	206 " 207	
3	10	" 65/01 " 27	"	28 " 29	
	11	" 65/176 " 193	"	194	
	12	" 65/195 " 212	"		
4	13	" 64/01 " 29	"	121 " 134 109 " 120	
	14	" 65/117 " 147	"		
	15	" 65/225 " 231	"		
	16	" 65/213 " 223		224	
	A	———		65/98 à 116	

N = Nuages

Figure 10. Example of a flight plan for the acquisition of historical aerial photographs.

The historical aerial photographs conserved at the RMCA mostly correspond to paper reproductions of aerial surveys performed during the 1940's and 1950's by local colonial, and later by Belgian and French geographical institutes. Overall, the quality of the paper photos is relatively poor, depending on the dataset and the photo band. This is due to low quality imaging (e.g., blurring effects, noisy chemical emulsion, under- and overexposure), aging effects (e.g., cracks, chemical alteration), non-optimal long-term archiving conditions (e.g., humidity spots and paper deformation), and/ or man-made damages (e.g., permanent marking, deformed photo surface due to pencil marking). Therefore, the scanning of the thousands of photographs was done through the setting up of a specific digitalization protocol associated with an in-house developed mass-scanning protocol (Figure 11).

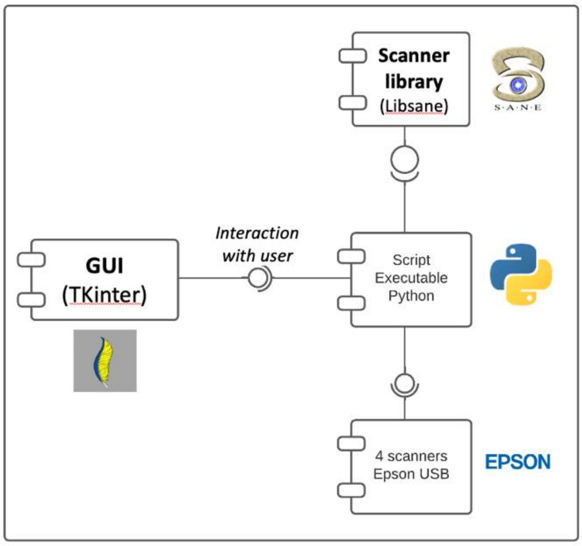


Figure 11. Mass-scanning infrastructure of the RMCA. Four flatbed photo scanners (photo on the left) digitise the historical aerial photographs in parallel, using the SANE library and a Python script (scheme on the right).

The scanning was performed according to the settings defined during the methodological tests of the first year, i.e., 1600 dpi, unsigned 16-bit and uncompressed TIFF images, with no grayscale stretching (i.e., full dynamic range of the scanner sensor).

<u>Digital image pre-processing</u>

The pre-processing of the digitized images, i.e., the standardizing of the images in terms of pixel size, resolution and location of the perspective centre, was improved thanks to the use of the Python language and the OpenCV and Pillow (PIL) libraries (Figure 12). The created scripts allow the easy and automatic pre-processing of the images in terms of orientation relative to the centre of perspective of the photo acquisition and the cropping of the photo edges based on a given distance from the fiducial marks. Hence, any type of aerial photographs can be processed, regardless of the location of the fiducial marks and the location of edges of the photographs in the scanned image. As most of the working time is spent in manually obtaining the coordinates (in pixel) of the fiducial marks to orient the photos, new Python scripts to automatize this step we implemented, but remain to be improved to be exploited. Once operational, they will strongly decrease the duration of the image pre-processing step. Another Python script has also been developed to optionally produce image masks, which enables hiding the fiducial marks and frame edges that are still visible in the standardized image datasets, during the photogrammetric processing. The final image pre-processing step, which corresponds to a downsampling of the photographs to a standard resolution of 600 to 1000 dpi, depending on the dataset, was previously performed with the Adobe Photoshop software, as its “bicubic sharper” algorithm. This step is now fully replaced by a two-step processing with Python and OpenCV, which (1) downsamples the images using a bicubic interpolation and (2) improves the final result using a CLAHE sharpening. This new downsampling approach improves the quality of the photo alignment and dense matching steps during the photogrammetric processing and is slightly better than the results obtained with the algorithm of Photoshop.

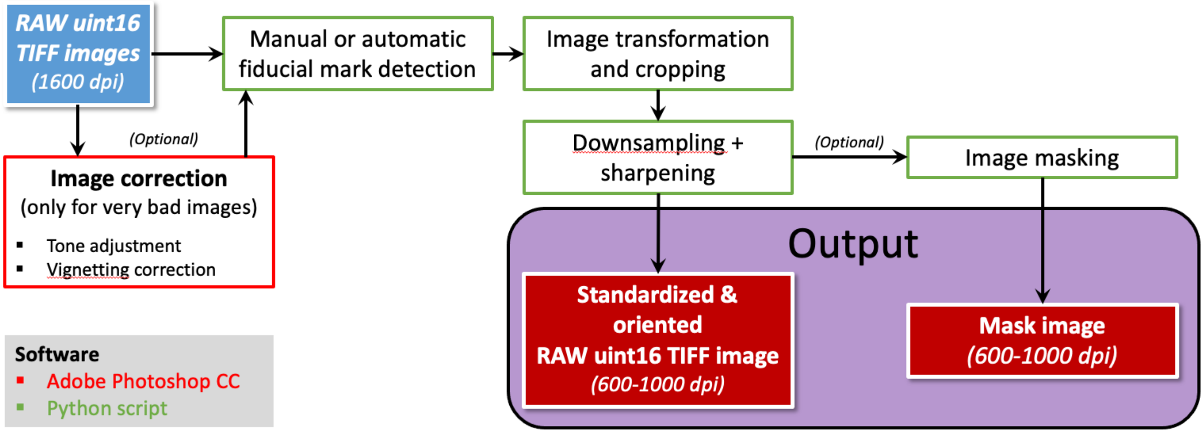


Figure 12. Image pre-processing workflow developed at the RMCA for the preparation of the historical aerial photographs for the photogrammetric processing.

Photogrammetric processing

The photogrammetric processing is performed with the Agisoft Metashape Pro software. Two processing workflows were developed, depending on the quality of the dataset. The first workflow is dedicated to high quality datasets, with photos having a good overlapping and very limited damages, from which it is possible to use the topographic information derived from the photographs. This workflow uses noise filtering, manual point removing and downsampling of the dense point clouds to improve the 3D reconstruction and get the best orthorectification possible. The software Cloud Compare is used in addition to Metashape Pro to improve the dense point cloud obtained during the processing. This first photogrammetric processing workflow is illustrated in Figure 13.

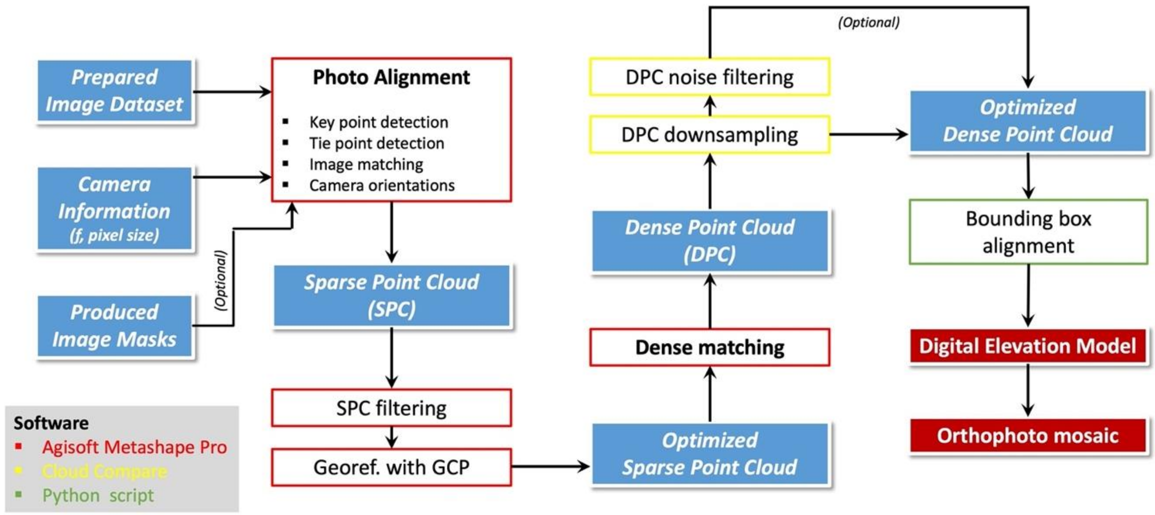


Figure 13. Initial photogrammetric processing workflow of the aerial photographs developed by the RMCA, which used for good quality datasets.

A second photogrammetric processing workflow is used when the topographic information retrieved from the photographs does not allow a proper orthorectification of the images, leading to significant errors in the produced orthomosaic. This is especially the case for damaged and poorly overlapping aerial photographs, and when the topography is complex, like in mountainous environment. In such cases, an external DEM is used for the orthorectification. Figure 14 summarises this second workflow and Figure 15 illustrates the improvement provided by it in mountainous environment.

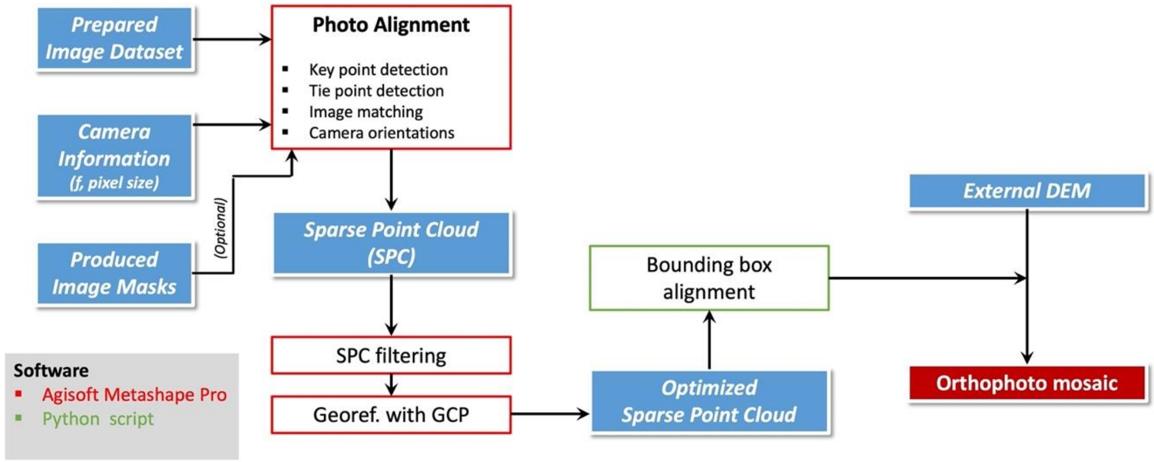


Figure 14. Second photogrammetric processing workflow of the aerial photographs developed by the RMCA for low quality datasets.

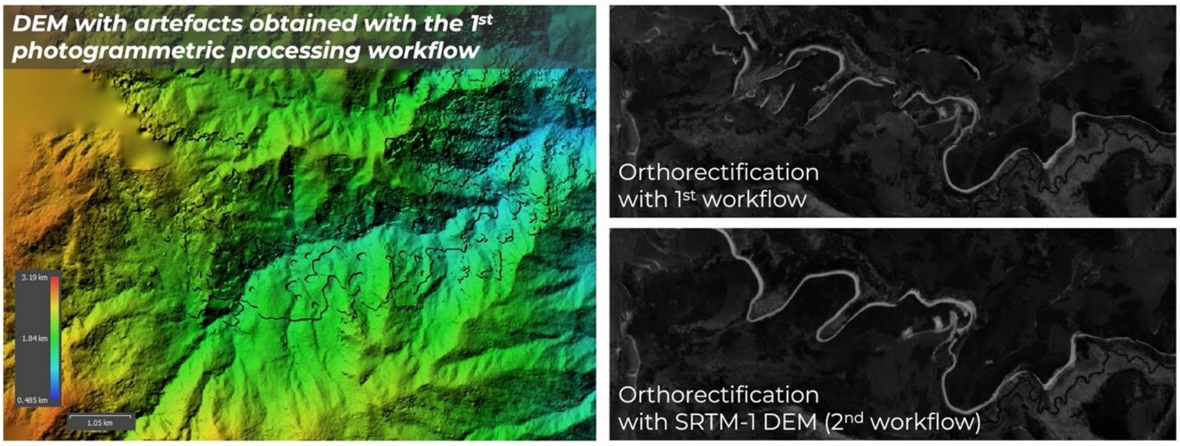


Figure 15. Comparison of the two photogrammetric workflows for low quality datasets, in mountainous environment. The left frame shows artefacts in a DEM derived from the aerial photographs, when image overlapping is insufficient. The frames on the right show how bad topographic reconstruction can lead to errors in the orthomosaic (top-right image), while an external DEM can solve most of these errors when it is used for orthorectification.

These photogrammetric processing workflows were applied on different datasets, providing DEMs and/or orthomosaics for WP3 to 8.

In order to assess the quality of the topographic reconstruction with photogrammetry (1st processing workflow), we used the Monte Carlo statistical approach developed by James et al. (2017) to estimate the precision of the photogrammetric reconstruction and georeferencing. This approach shows that we can obtain a mean precision of 2 (XY) to 10 (Z) m in the 3D reconstruction (photogrammetric and geoferencing precisions combined) when we can get access to accurate ground control points extracted from recent 3D imagery, like Pléiades tri-stereo images or drone surveys. The precision strongly decreases when Google Earth or Bing imagery combined with SRTM-1 DEMs are used. This highlights the importance of obtaining accurate control points to improve both the camera calibration and the georeferencing of historical aerial datasets devoid of calibration report, especially when the aerial photographs are aged and damaged.

<u>Orthomosaic products:</u>

Orthomosaics were created for the areas displayed in Figure 9. Most of them have a spatial resolution of ~1 m. Although this is an unprecedented level of details for such a period, we have to keep in mind that the exploitation of these products comes with quality caveats. First, as already stressed earlier, the quality of the paper photos is usually relatively poor. Second, the orthomosaics are based on scanned photos that already are photo reproductions. Consequently, additional blurring, vignetting effects, bad exposure and optical distortions are observed. Third, the quality of orthomosaic production is limited due to the absence of camera calibration reports associated with the aerial datasets and the unavailability or insufficient number of precise ground control points for proper georeferencing and orthorectification of the data.

In addition to the production of orthomosaics based on historical aerial photographs, a recent orthomosaic and DEM of the city of Goma and its vicinity was produced using 6550 photographs taken during a helicopter flight, in June 2017. A first version of these images was published by Smets et al. (2018), but was further improved with ground control points of higher quality obtained during a field survey in March 2018. The final orthomosaic and DEM cover an area or about 140 km^2 and have a spatial resolution of 17.5 and 35 cm, respectively. (Manuscript in supplementary material)

Maps and archives

Most of the entire collection of maps available at RMCA have been scanned (more than 30,000 documents). Among those, several hundreds of document are available for the PAStECA region. An overview of the data is provided through the RMCA Geocatalogue. The Geocatalogue has its roots in another project but benefited from a key contribution from PAStECA.

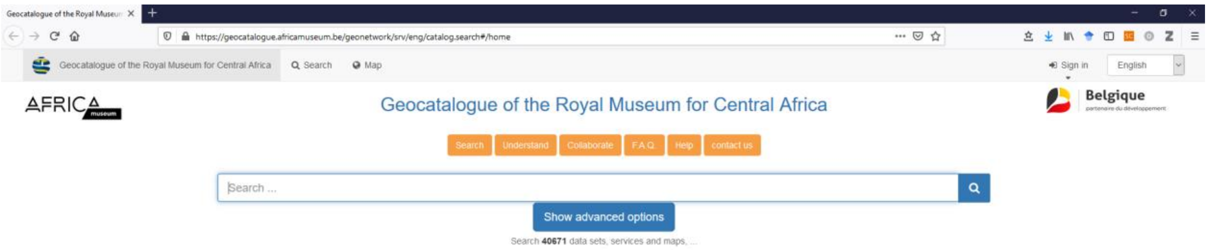


Figure 16. The Geocatalogue online platform developed by the RMCA.

4.2. Mapping land use and land cover form black and white aerial photographs (WP3)

Generation of LULC from historical black and white aerial photographs

First, methodology for using deep learning (fully convolutional networks (FCNs)) and OBIA (Object-Based-Image-Analysis) was created using aerial RGB images only as input (Mboga et al., 2019). This RGB image was the helicopter-based very high-resolution (VHR) imaging of Goma (Figure 17; Smets et al., 2018). This first step of the analysis was key for the development of a methodology based on deep learning using fully convolutional networks for land cover classification from historical black and white photographs (Figure 18). Further, a historical landcover map for three cities in central Africa are generated (Figure 19).

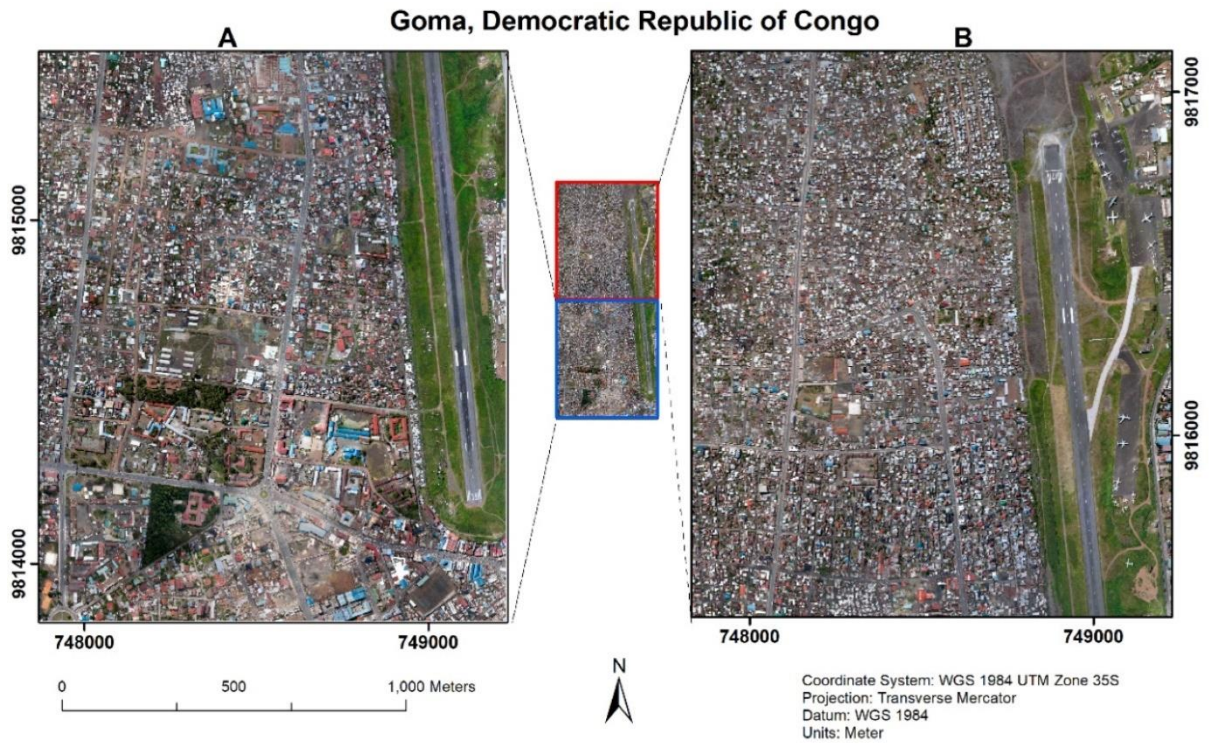


Figure 17. Map illustrating the study area of Goma, Democratic Republic of Congo. The training and testing data are generated from Tile A and Tile B respectively. The image is from Smets et al. (20198). The figure is from Mboga et al. (2019, manuscript in supplementary material).

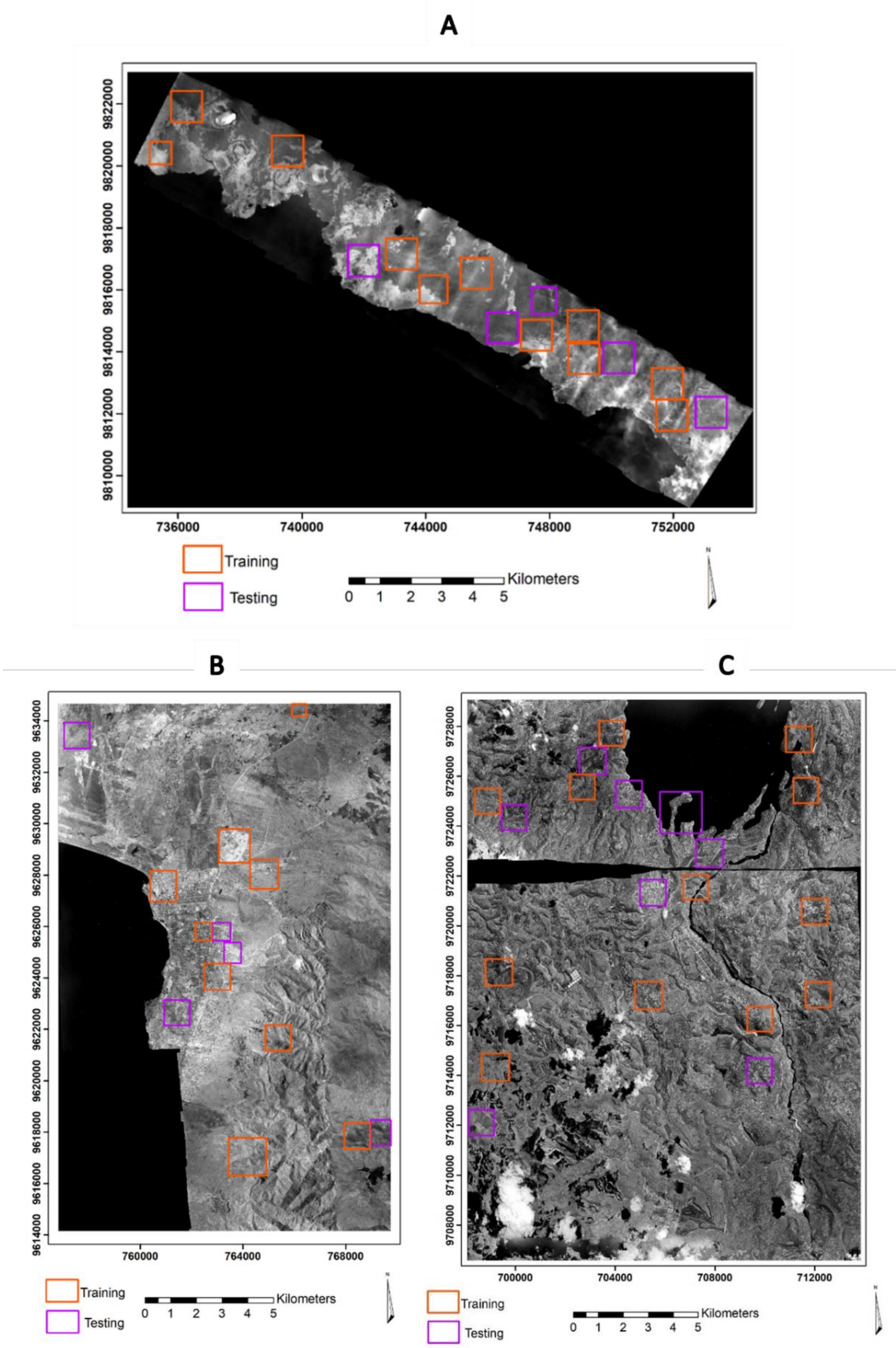


Figure 18. Locations of the training and testing tiles in the images of (A) Goma-Gisenyi, (B) Bujumbura and (C) Bukavu used in the experiments covering a geographical area of 80 km2, 265 km2 and 258 km2 respectively. Figure from Mboga et al. (2020, manuscript in supplementary material).

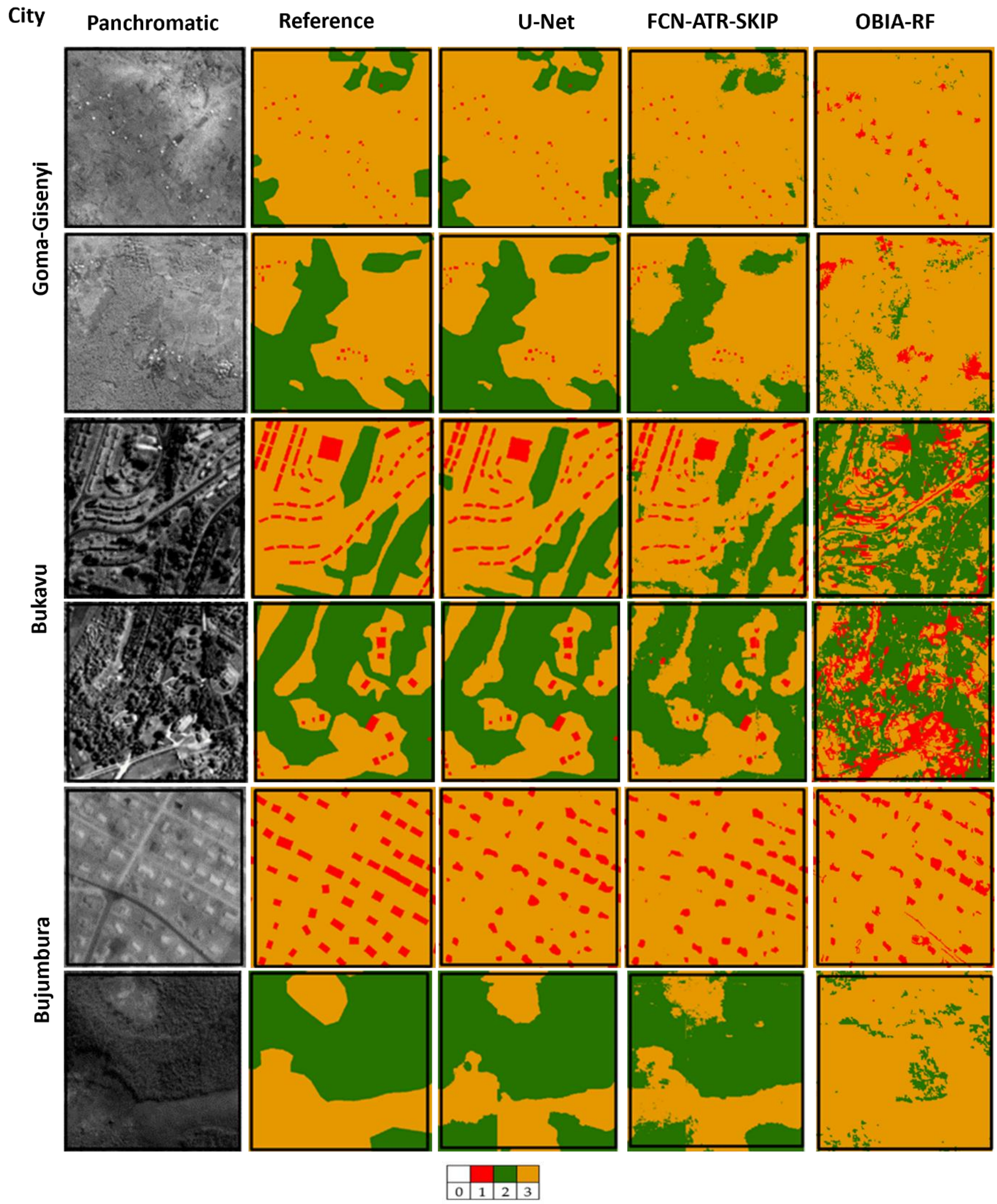


Figure 19. Sample classified scenes the city of Goma-Gisenyi, Bukavu, and Bujumbura after using the FCN-ATR-SKIP, U-NET and OBIA-RF. The classes displayed are (1) building (2) high vegetation, and (3) mixed bare land and low vegetation. Four subclasses of the mixed and Bare class have been grouped. 0 represents the unclassified pixels. Figure from Mboga et al. (2020, manuscript in supplementary material).

The developed methodology provides an important step in proving the utility of digitised analogue archives for support of modern environmental scientific research. High quality landcover maps were generated as shown in Figure 3 but a major bottleneck in the use of deep learning approach was the amount of effort needed in generating labelled reference data to train the models. Consequently, we pursued a transfer learning strategy that aims to minimise the amount of reference labels required, also referred to as domain adaptation.

Transferability and generalization

This work was carried out in partnership with Ecovision Lab, ETH Zurich, during a research visit that took place in February-March 2020 (Mboga et al., 2021). We explored unsupervised domain adaptation for semantic segmentation applied on remote sensing images with a novel use-case on interpretation of historical aerial photographs. The domain adaptation methods focus on the alignment of data distribution in the feature space between the source and the target domains (Figure 20). In the work we compare two unsupervised domain adaptation methods for the task of land-cover mapping and evaluate the added benefits of fine-tuning the domain adaptation networks using small amounts of data from the target domain.

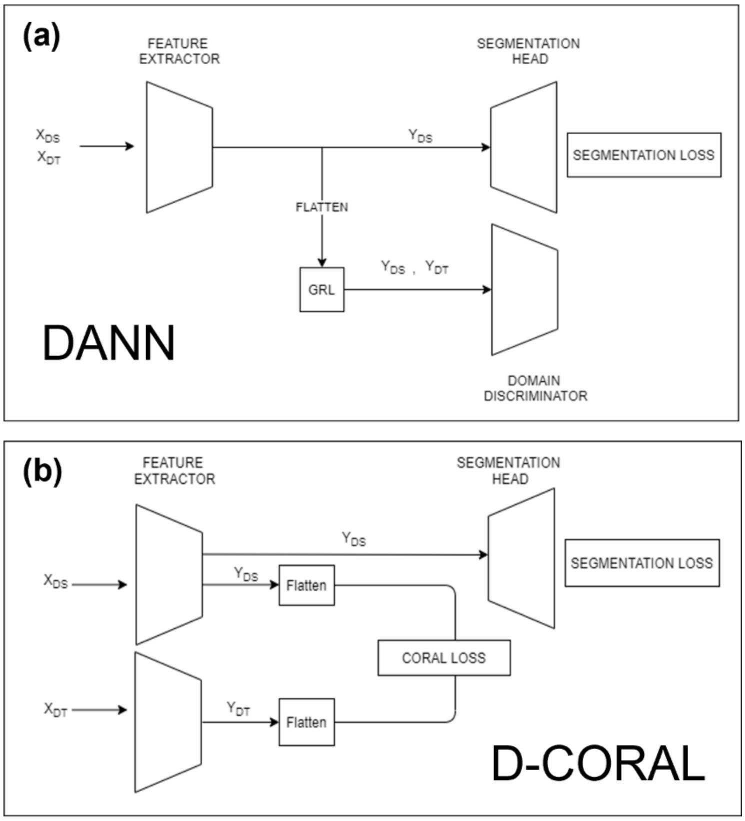


Figure 20. Diagrams of the Domain adversarial neural network (DANN) and the correlation alignment adversarial network (D-CORAL) investigated in the work.

From the numerical and qualitative results, unsupervised domain adaptation is not adequate to provide sufficient improvement in the classification accuracy as close as when the reference data is available in the target domain. However, fine-tuning experiments show that some benefits of domain adaptation can be gained when a small training set is available from the target domain. Quality of raw data undoubtedly affects the robustness of the classification algorithms. Pixel-wise landcover classification (semantic segmentation) was a complex task and adversely affected by the spectral quality of the data. Future works would entail exploring a land-use problem that involves labelling a patch instead of each pixel in that patch. Further details can be found in Mboga et al. 2021, manuscript in supplementary material).

4.3. Mapping land use and land cover changes (WP4)

At the regional level:

We applied the photogrammetric procedures described in WP2 and the deep learning algorithms developed in WP3 to automatically extract the 1958 forest cover for the entire Kivu Rift. In a first step, nearly 2,400 historical photographs and more than 1,043 ground control points were used to create a panchromatic orthomosaics with a resolution of 1 m and covering more than 21,000 km^2 (Figure 21). In a second step, we used a fully convolutional network to identify forest. Finally, we visually screened the product and corrected the most obvious misclassifications (typically urban structures misinterpreted by the algorithm as trees). As such, the final forest map has an accuracy of 96.7 % (Figure 21). The regional evolution of forest cover changes was then assessed by comparing the 1958 forest cover with 1988, 2001 and 2016 data (Figure 32c).

Most of the forests in Rwanda and Burundi had already been converted into agricultural land by 1958, with the remaining forests covering ~19% and ~29% of the total land surface area, respectively (Figure. 21). Large-scale deforestation had been necessary to sustain the at-the-time already large population in Rwanda and Burundi (on average 94 inhabitants per km2 in 1958) and to remediate recurrent food crises44. In the eastern DR Congo, population pressure was much smaller, as the average density in the wider Kivu region was estimated at only 17 inhabitants per km2 in 1958 (Meditz and Merrill, 1994; population.un.org/wpp/). As a result, forests still covered 70% of the countryside in the DR Congo west of Lake Kivu in 1958.

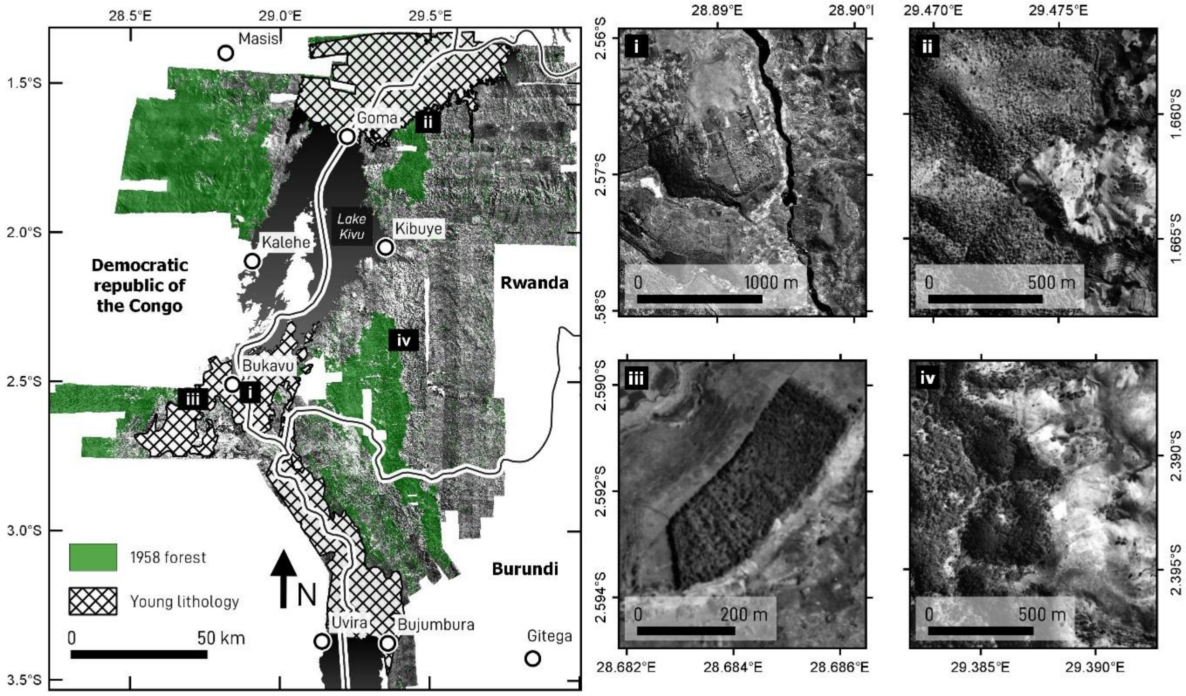


Figure 21. The 1958 orthomosaic and forest cover for the Kivu Rift. Locations on the map: (i) Ruzizi River near Bukavu (28.8914° E, 2.5687° S); (ii) eastern edge of Gishwati Forest (29.4750° E, 1.6627° S); (iii) planted forest west of Bukavu (28.6844° E, 2.5919° S); and (iv) eastern edge of Nyungwe Forest (29.3879° E, 2.3925° S). Our study area is confined by the extent of the historical photographs and excludes areas of young lithology (volcanic rocks and river and lake sediments). Figure from Depicker et al. (2021b, manuscript in supplementary material).

Besides the historical photographs, we have access to a range of regional and continental datasets to assess historical forest coverage. We use the regional land-cover maps for 1988 and 2001 provided by Basnet and Vodacek (2015). These maps are provided at a 30 m resolution and were derived from Landsat imagery. The overall accuracy of the maps is reported to be at least 90% (Basnet and Vodacek, 2015). We reclassified the land-cover maps into forest-cover maps by merging the following land-cover classes: (1) ‘forest’ and (2) ‘open/degraded forest’. The 2016 forest cover is extracted from the continental European Space Agency Climate Change Initiative (ESA-CCI) prototype land-cover model, provided at a 20 m resolution and derived from Sentinel observations (ESA, 2017). Contrary to the regional land-cover maps from Basnet and Vodacek (2015), the accuracy of the ESA-CCI model within the Kivu Rift is unknown. We assess the accuracy of its ‘forest’ land-cover class by validating 500 forest and 500 non-forest points. These points are randomly sampled in areas where Google Earth has imagery available for the year 2016, so that these 1,000 points can be validated for the correct time period. We estimate the 95% confidence interval of the accuracy by recalculating it 1,000 times, each time sampling 500 forest and 500 non-forest points (with replacement) from our validation dataset. As such, we observe an accuracy of 86.1 ± 2.1%. Further details can be found in Depicker et al. (2021b, manuscript in supplementary material).

A the level of the three urban areas:

We use a unique 60-year timeseries of data comprising landcover maps from historical orthomosaics produced for each city (see Section 4.3, Mboga et al., 2020) and Landsat archives from 1972 to 2020 (See Supplementary Methods S1 in Mboga et al., in review). Binary built-up masks based on these landcover maps are used to compute the Landscape expansion index (LEI) for a dynamic characterization of the built-up area patterns. The built-up area landcover represents a settlement mask, comprising of manmade structures i.e., buildings, streets, and impervious surfaces that act as a proxy for an urban area . Three types of built-up area patterns (Figure 22) are identified namely 1) infilling-areas surrounded by an existing urban area, 2) edge expansion-areas extending from the margins of an existing urban area and 3) outlying-areas not spatially connected to an existing urban area. Further details can be found in Mboga et al. (in review, manuscript in supplementary material).

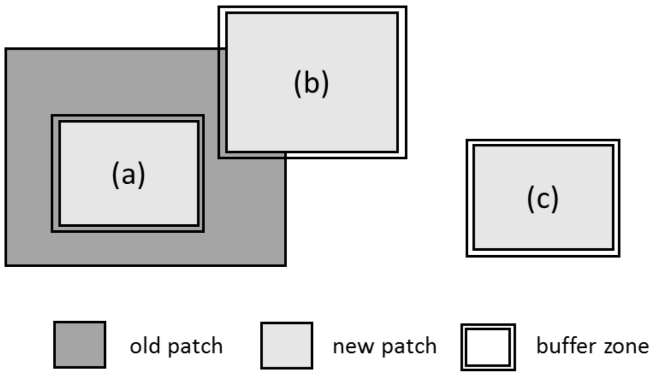


Figure 22. Three types of landscape expansion namely a) infilling, b) edge-expansion and c) outlying. Figure from Mboga et al. (in review) (manuscript in supplementary material).

The built-up area increased from less than 1 km^2 to 74 km^2 in Goma (1947-2020), 6 km^2 to 109 km^2 in Bujumbura (1959-2020) and 2 km^2 to 34 km^2 in Bukavu (1959-2020) (Figure 23 and Table S7 in Mboga et al., in review, supplementary material).

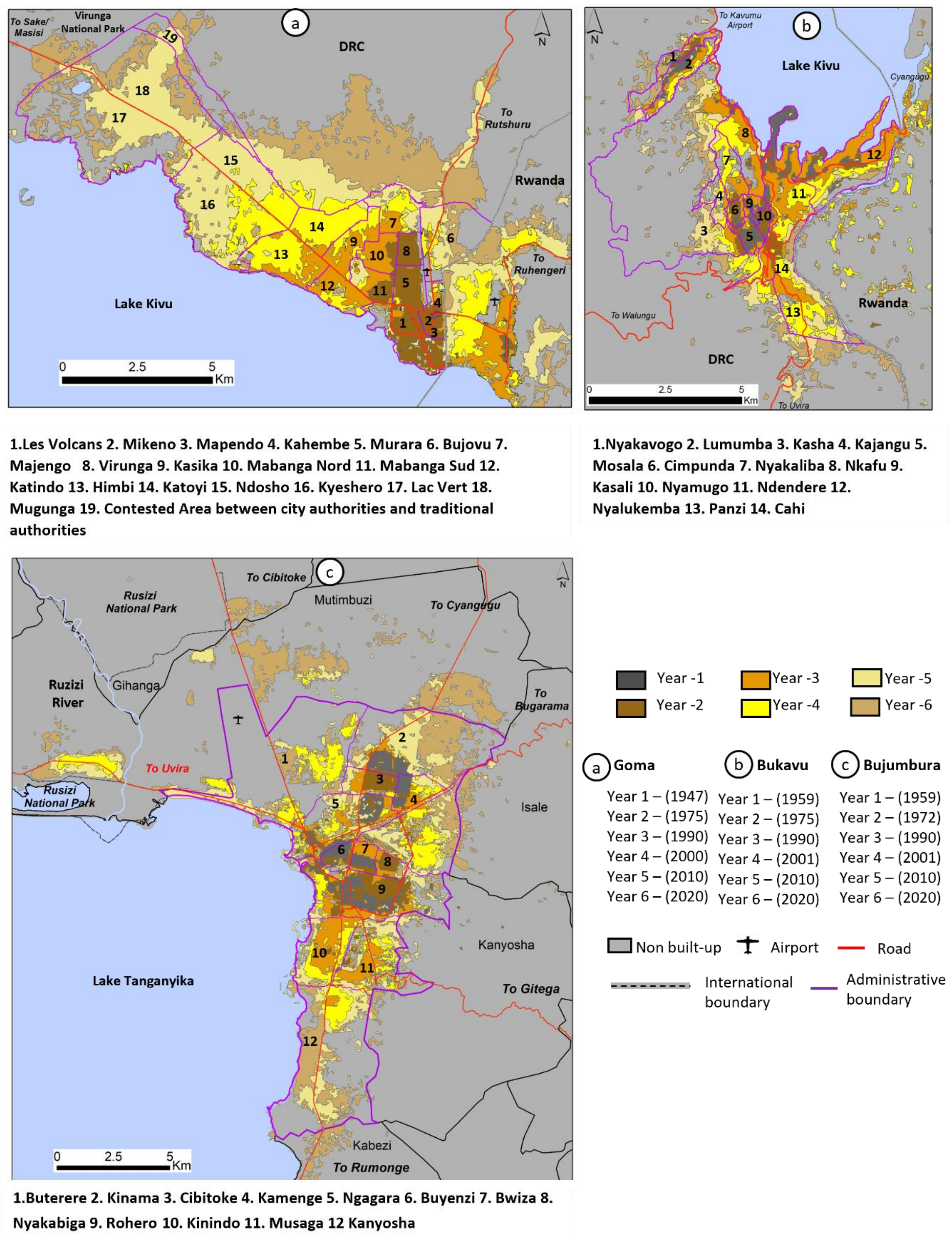


Figure 23. Location and amount of built-up land development for a) Goma, b) Bukavu, and c) Bujumbura. For each of the cities the names of the districts are provided. Figure from Mboga et al. (in review, manuscript in supplementary material).

4.4. Earth surface processes and land degradation (WP5 & 7)

<u>At the regional level:</u>

Our research was carried out in several steps that are interconnected:

Step 1: We focus on the regional understanding of the landslide occurrence and activity and also their distribution with regard to current static environmental conditions. Therefore, here we do not use historical photographs and archives. However, this knowledge of the current landside patterns is a major step for the analysis of the trends in landslide occurrence, activity, and their distribution regarding longer-term forest dynamics that will be unravelled through the use of the historical photographs.

For the inventory we used Google Earth imagery (Figure 24). The mapping (with 3D view activated and elevation exaggeration of 1) was done manually for all landslides, and both source and deposit (runout) areas were delineated as polygons. For the old landslides that are covered with vegetation, this was the only option since automatic detection approaches would not work. For the recent and active ones, this was done to avoid amalgamation (Marc and Hovius 2015). Also, a distinction is made between shallow and deep-seated landslides with the latter being > 5 m deep. This parameter of depth is important to consider in our research since the occurrence of shallow movements is much more sensitive to varying surficial landscape environments (e.g. LULC changes) and rainfall conditions (Sidle and Bogaard 2016). In addition, shallow landslide signatures disappear more quickly from the landscape (Sidle and Bogaard 2016).

An extensive inventory of > 6000 landslides has been compiled for the entire western branch of the East African Rift. Landslides are diverse in size (from a few tens of m^2 to 40 km^2—Fig. BBB), shape and process (categorized according to Hungr et al. 2014). They appear in various environments (urban areas, rural areas, pristine forests). The approach is regional and the inventory is built based on a trade-off between a search time per cloud-free area and inventory details. The database contains detailed information such as the timing of the feature, typology of the landslide process, connection to drainage systems, mining activity, and road connectivity. This database has been used to assess the regional landslide susceptibility (Figure 25). In this work we highlight the main controls of the environmental factors on landslides. We also demonstrate that there is a real added value of building a regional landslide susceptibility model as compared to continental and global scale available products. Further details can be found in Depicker et al. (2020, manuscript in supplementary material). Note also that this susceptibility model developed in PAStECA was used to be applied at a larger scale for studying the rainfall thresholds associated with the occurrence of landslides in the western branch of the East African Rift (Monsieurs et al., 2019, manuscript in supplementary material).

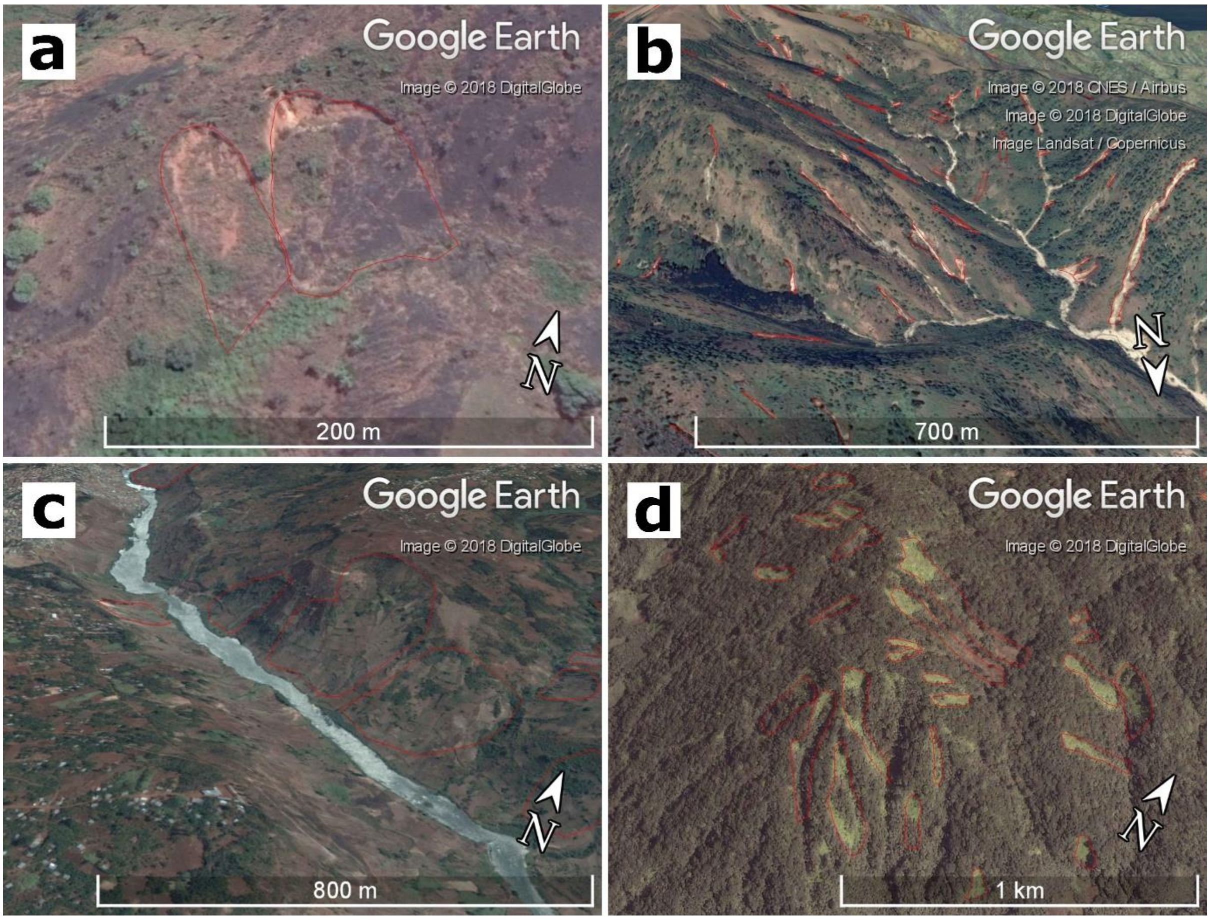


Figure 24. Oblique views of landslides in Google Earth imagery. The scales are approximate: (a) rotational slides, DR Congo (−3.960◦S, 28.927◦E), (b) debris flows and debris slides triggered by rainfall, Tanzania (−4.479◦S, 29.698◦E), (c) rotational slides at the Ruzizi river near Bukavu (DR Congo) and Rwanda (−2.554◦S, 28.882◦E), (d) rainfall triggered landslides in rainforest (event 26 in Fig. 2), DR Congo (−2.603◦S, 28.156◦E). Figure from Depicker et al. (2020, manuscript in supplementary material).

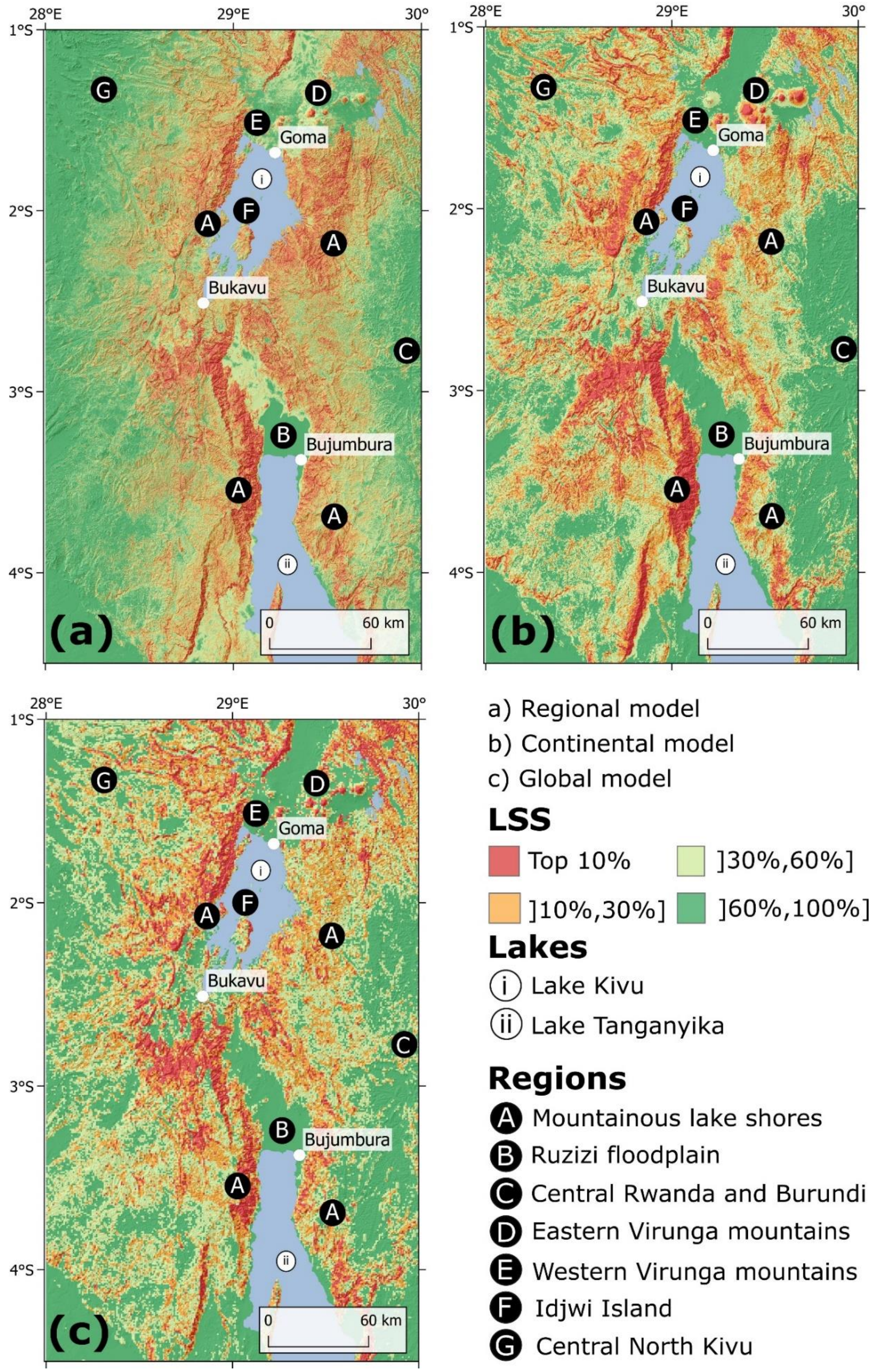


Figure 25. Standardised LSS for regional and global models: (a) the regional combined model, (b) the continental model of Broeckx et al. (2018), and (c) the global model of Stanley and Kirschbaum (2017). Figure from Depicker et al. (2020, manuscript in supplementary material).

Step 2: the landslide database in step 1 was updated using Google Earth imagery and based on a 2018 field mission in Rwanda. The updated inventory contains > 12,000 landslides. We further made a distinction between deep-seated and shallow landslides, and between recent and old landslides. As such, we identified ~8,000 recent shallow landslides for which we could estimate the timing of occurrence. Using this database, we investigated the impact of deforestation on shallow landslides, while accounting for biases in Google Earth imagery (for which we developed a new methodology) and other environmental factors such as tectonic uplift and rock strength (Figure 26) (Depicker et al., 2021a). We find that shallow landslide erosion rates in these rejuvenated landscapes are roughly 40% higher than in the surrounding relict landscapes. In contrast, we find that slope exerts a stronger control on landslide erosion in relict landscapes. These two results are reconciled by the observation that landslide erosion generally increases with slope gradient and that the relief is on average steeper in rejuvenated landscapes. The weaker effect of slope steepness on landslide erosion rates in the rejuvenated landscapes could be the result of three factors: the absence of earthquake-induced landslide events in our landslide inventory, a thinner regolith mantle, and a drier climate. More frequent extreme rainfall events in the relict landscapes, and the presence of a thicker regolith, may explain a stronger landslide response to deforestation compared to rejuvenated landscapes. Overall, deforestation initiates a landslide peak that lasts approximately 15 years and increases landslide erosion by a factor 2 to 8. Eventually, landslide erosion in deforested land falls back to a level similar to that observed under forest conditions, most likely due to the depletion of the most unstable regolith. Landslides are not only more abundant in rejuvenated landscapes but are also smaller in size, which may again be a consequence of a thinner regolith mantle and/or seismic activity that fractures the bedrock and reduces the minimal critical area for slope failure. With this step 2, we highlight the importance of considering the geomorphological context when studying the impact of recent land use changes on landslide activity. Further details can be found in Depicker et al. (2021a, manuscript in supplementary material).

The understanding of the role of deforestation on landslide occurrence and the importance of the geomorphic context (rejuvenated/relic landscape) are key issues that are taken into account on the risk trend analysis (see Section 4.5).

Step 3: Using the regional orthomosaics, we look at how landslides identified in steps 1&2 look like in the 1950's (Figure 27). We could quantify how many new landslides have occurred since then (Figure 28). These observations on the historical photographs allowed to assess in the multi-decadal regional landslide mobilisation rates. Landslide mobilisation rate is here defined as the total volume or mass (derived from the landslide surface area and depth) of sediments per unit area and per unit of time. We find that the average mobilization rate in the landscapes rejuvenated by the retreat of rifting-related knickpoints is three times higher as compared to the relict landscapes. These mobilization rates are dominated by deep-seated landslides; shallow landslides, although more frequent, being generally smaller. Our mobilization rates are relatively low as compared to observations in other mountainous regions. Yet, the tropical NTK rift also has a more moderate topography and degree of tectonic activity. In addition, our research covers a unprecedented large area and a long period, as such being not biased by local extreme events. Overall, this research focuses on a type of environment for which few observations are currently available. As such, this work helps to bridge an important data gap.

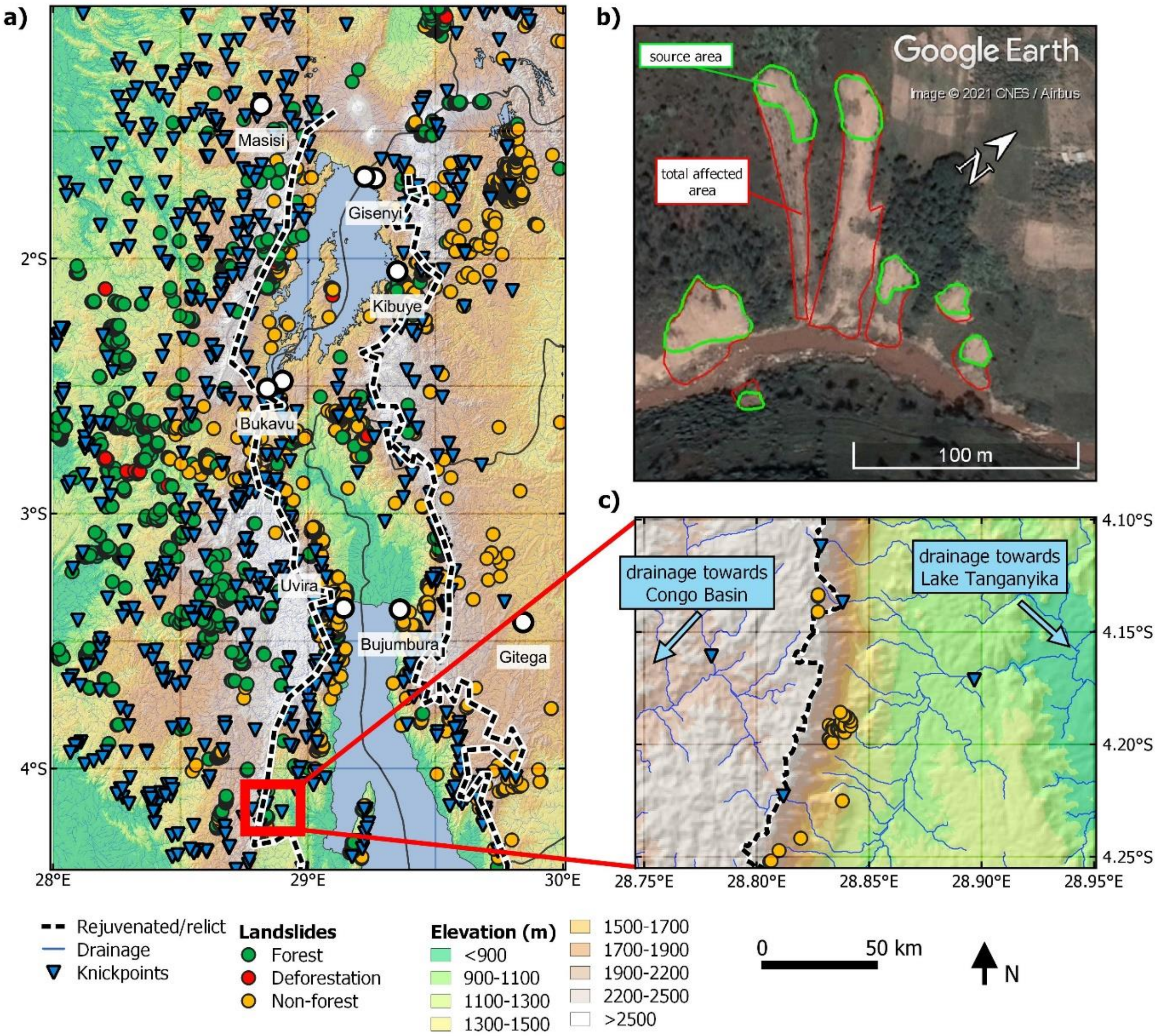


Figure 26. Landslide and knickpoint inventory for the NTK rift. (a)We identified 7994 shallow recent landslides that occurred either in forest, non-forest, or after deforestation and 673 non-stationary knickpoints. These knickpoints were used to separate the rejuvenated landscapes between the rift shoulders from the surrounding relict landscapes (black and white line). (b) Example of shallow landslides in Rwanda (-1.7151 S, 29.7909 E) and the delineation of their total area (red) and source area (green). (c) Example of the rift shoulder west of Lake Tanganyika. Figure from Depicker et al. (2021, manuscript in supplementary material).

We could also assess the impact of deforestation, mining activities and road constructions (Figure 2a) on these mobilisation rates. In rejuvenated landscapes, roughly 5% of the sediment mobilization by landslides is linked to human activity, while in relict landscapes this figure rises to 18%, notably due to mining and road construction. The role of human activity is limited as compared to the recent occurrence of some large landslides, which seem linked to natural causes and dominate the overall mobilization rates. Moreover, the limited role of human activity must be balanced with the fact that the NTK Rift, although highly populated, remains relatively untouched by major road infrastructure constructions. While previous studies have found that deforestation has a large impact on the landslide risk in the region, its impact on the mobilization rates is much less important. Overall, our results significantly contribute to a better understanding of landslide mobilization and its controlling factors in the context of human-induced environmental change, especially by providing much-needed long-term observations for a currently under-researched type of environment. Further details can be found in Depicker et al. (to be submitted, manuscript in supplementary material).

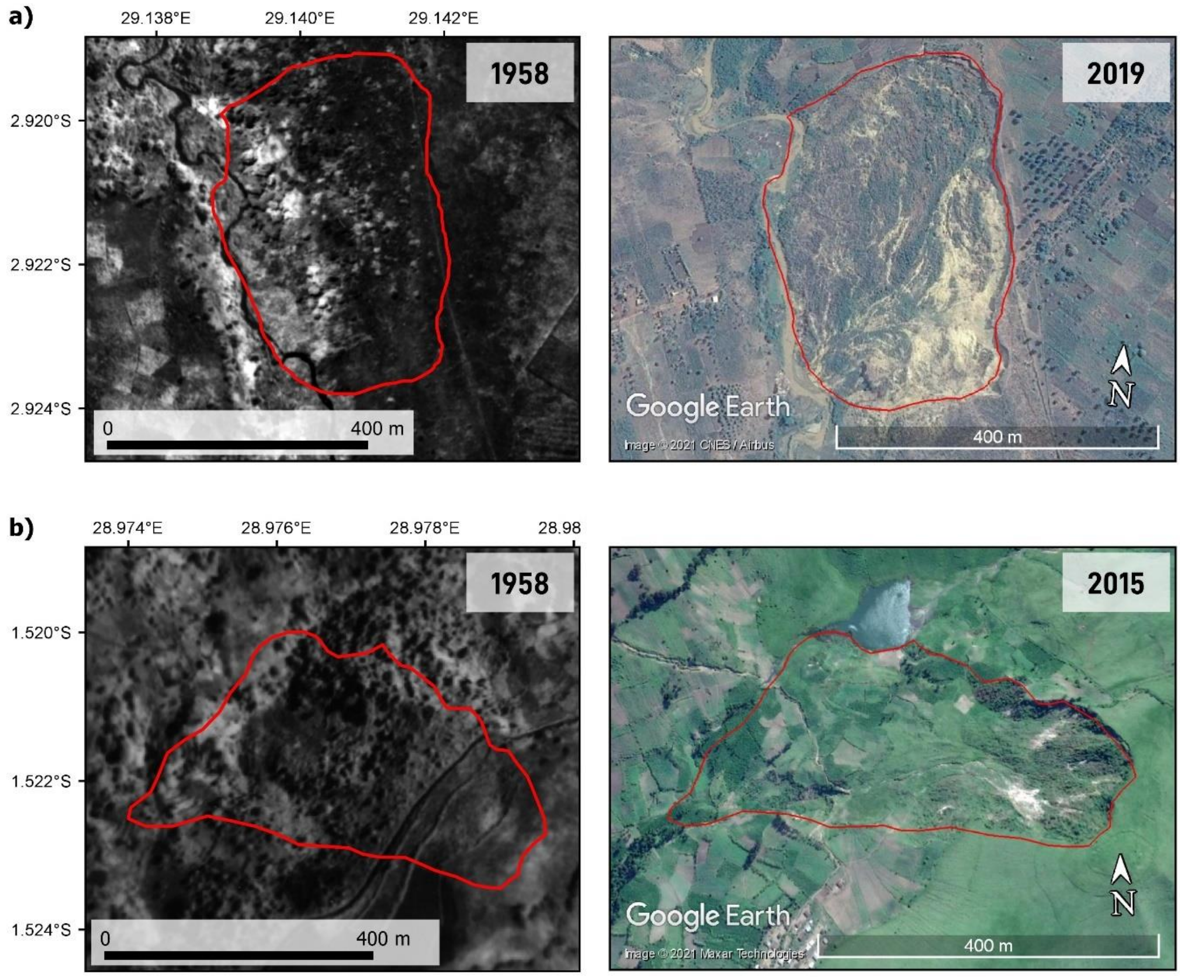


Figure 27. Examples of recent deep-seated landslides. a) Recent landslide along a tributary river of the Ruzizi, Burundi. b) Recent deep-seated landslide south of Masisi, Democratic Republic of the Congo. The landslide deposits form a dam in the river, creating a small lake. Figure from Depicker et al. (to be submitted, manuscript in supplementary material).

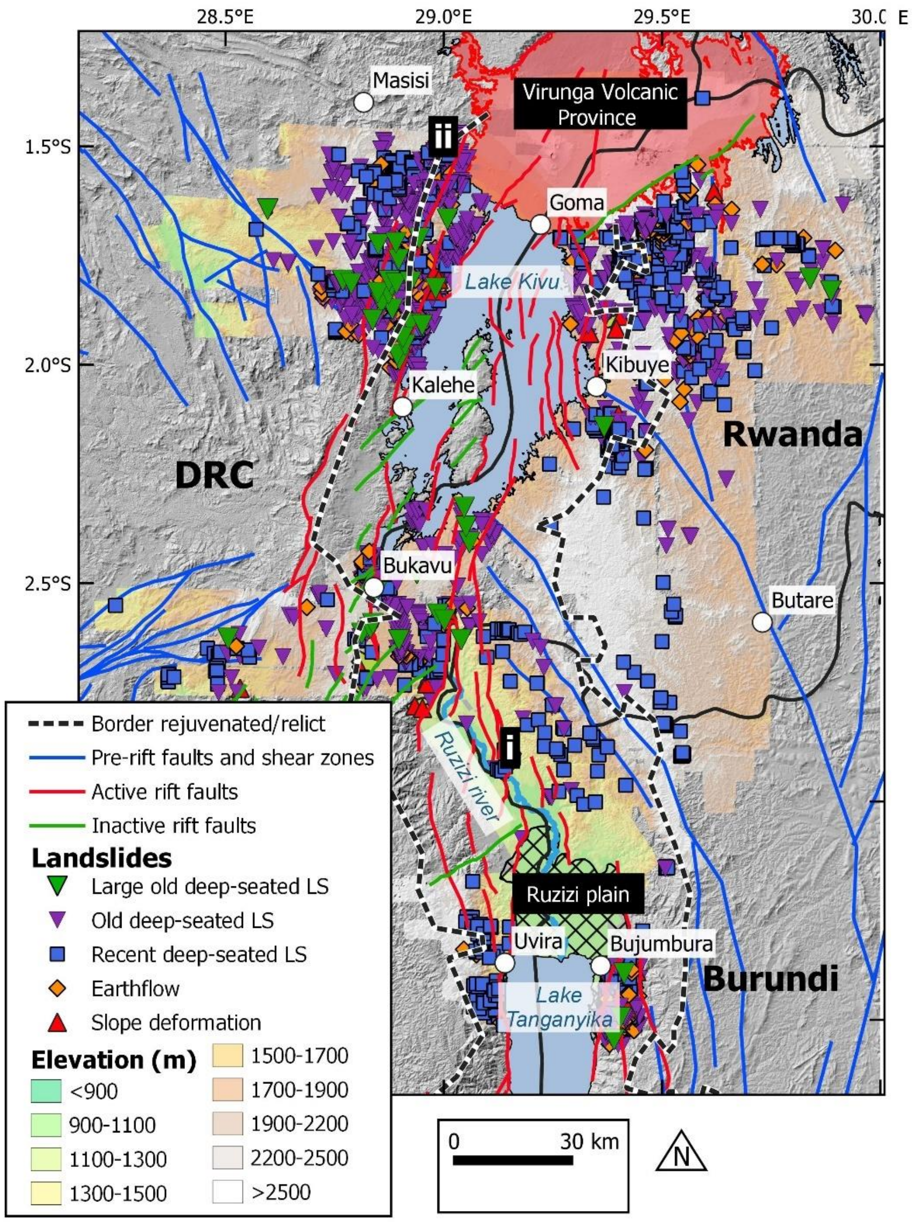


Figure 28. The multi-temporal deep-seated landslide inventory, containing old deep-seated landslides (prior to the year 1958) and recent deep-seated landslides (between 1958 and 2019). We visualize the border between the rejuvenated landscapes (inside the Rift shoulders) and the surrounding relict landscapes. The red and green lines indicate the active and inactive faults that drove the Rift formation. The blue lines represent reactivations of pre-rift faults (Delvaux et al., 2017). Figure from Depicker et al. (to be submitted, manuscript in supplementary material).

At the city level: Bukavu and Bujumbura:

For the urban focus, we combined a more careful analysis of Google Earth imagery interpretation than for the regional study, with extra topographic products (Digital Elevation Models) we derived from Pléiades satellite images, careful field investigation and local people interviews. In addition, we used the historical aerial photographs and any available other archives that could help us to leverage the story of the landslides and the landscape.

For Bukavu, we identified more than 100 landsides that cover ~30% of the urban territory (Figure 29). We were able to make a distinction between various ages of landslides and see that they are different stage of activity. We could also evidence that the local geodynamics of the rift and the formation of Lake Kivu played a role in the presence of these, sometimes large (> 1km²) landslides. The analysis of the historical photographs was key in our analysis that shows that the relation between slope instability triggers and slope failure is not always straightforward and that the role of intrinsic evolution of the hillslope must not be ignored when assessing landslide hazard in tropical mountainous regions (Dille et al., 2019). This role of the weathering in the occurrence of slope failure could also partly explain the cluster of large landslides in Bukavu (Figure. 1). Analysis of landslide causes and triggers provided here should help improve the understanding of how surface processes influence the pace of hillslope evolution. It also contributes to a more accurate evaluation of the landslide hazard in the area and across other regions where similar environmental conditions are met. In addition to the focus on the natural processes at the origin of the landslides in Bukavu, we could demonstrate for the Funu landslides, i.e. the largest and most inhabited landslides of the city, that over decadal timescales, we find that the sprawl of urbanized areas (Figure 30) led to the acceleration of one of its section, which was probably driven by self-reinforcing feedbacks involving slope movement, rerouting of surface water flows and pipe ruptures (Dille et al., 2022). As hillslopes in many tropical cities are being urbanized at an accelerating pace, better understanding how anthropogenic activity influences surface processes will be vital to effective risk planning and mitigation.

For more information on the landslide map at the city scale, see Dewitte et al. (2021, supplementary material). For more information on the natural origin of the landslides, see Dille et al. (2019, supplementary material). For more information on the role of urbanization on the dynamics of large landslides, see Dille et al. (2022, supplementary material).

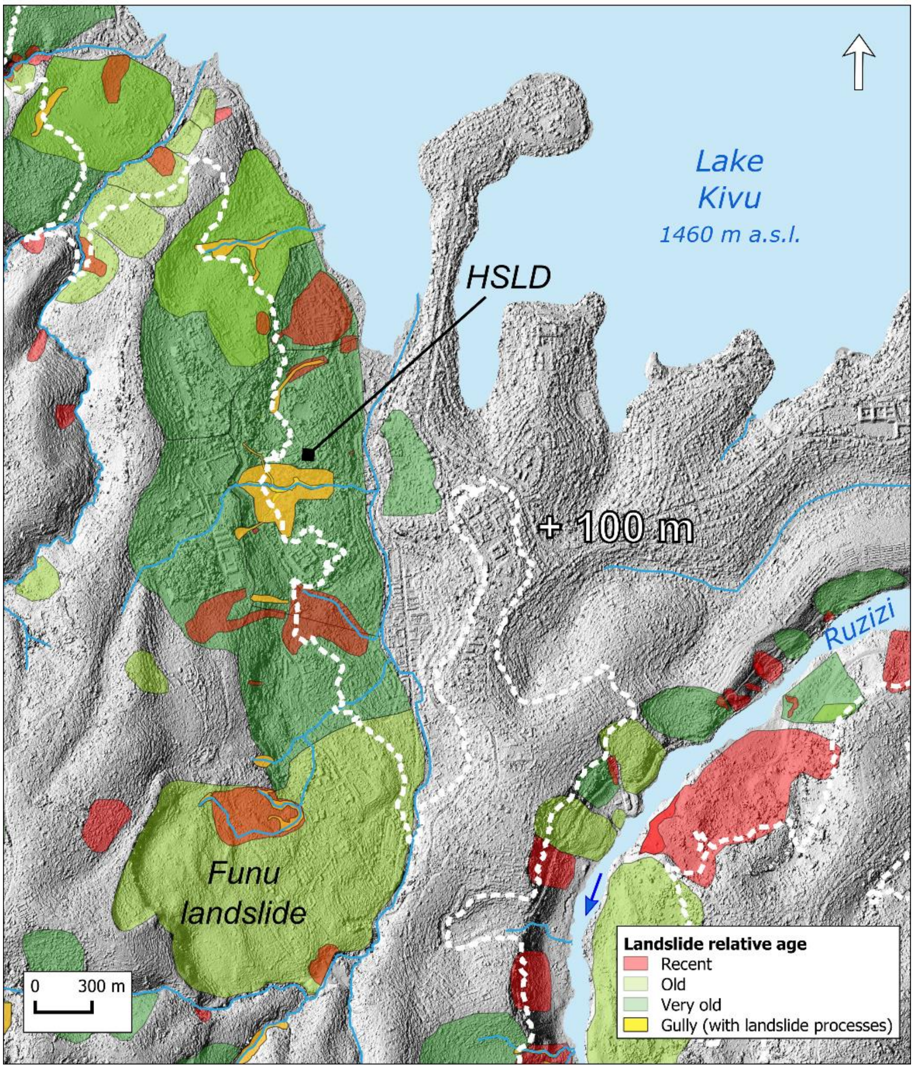


Figure 29. Landslides in Bukavu, their relative age (see text for details) and distribution with regard to Holocene lake highstands (+ 100 m, dashed white contour line). HSLD, highstands lacustrine material deposit. Hillshade derived from 1-m resolution DSM built from Pléiades tri-stereo images of 2013. It highlights the dense urban fabric of the city centre. Figure from Dewitte et al. (2021, manuscript in supplementary material).

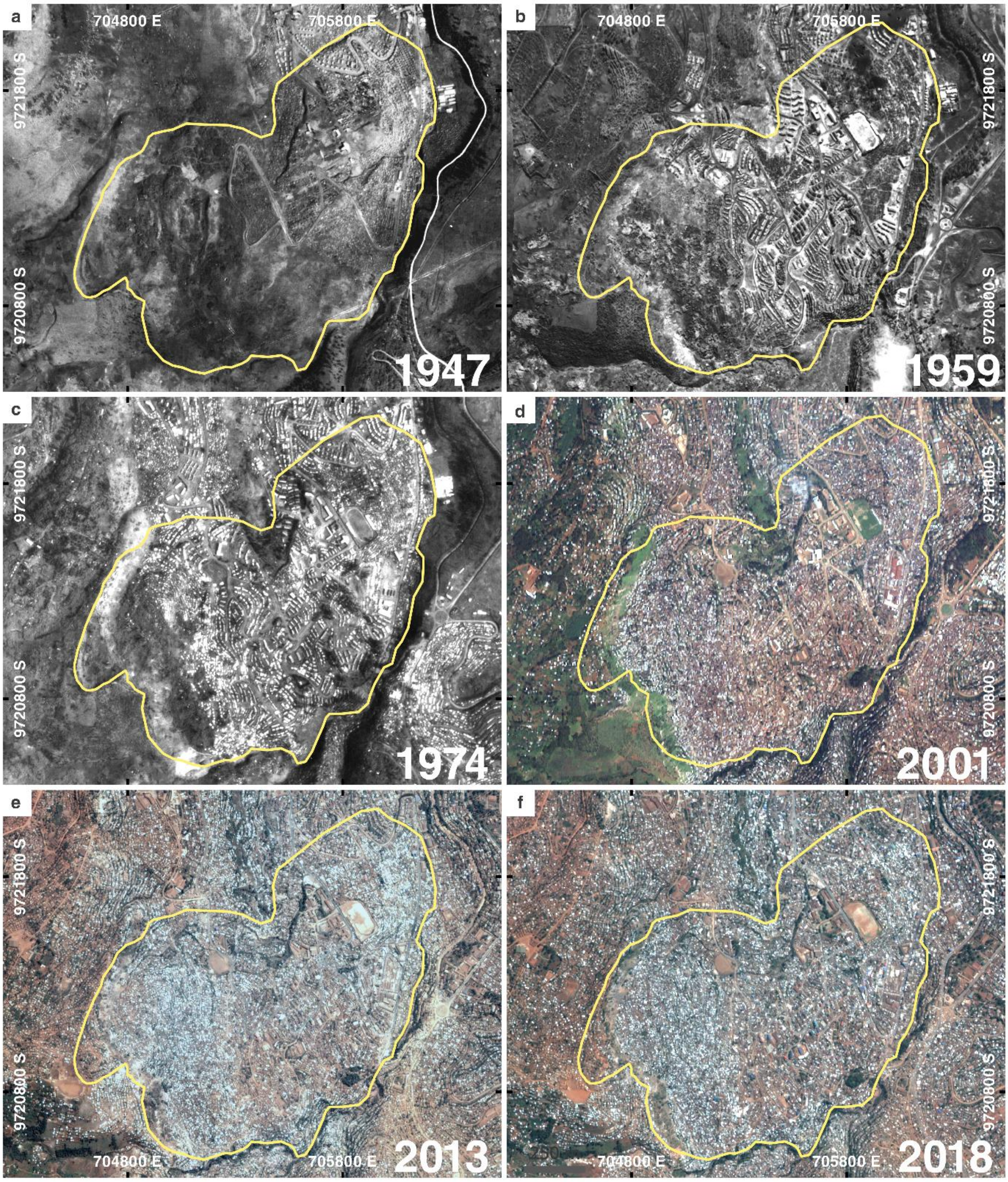


Figure 30. Progressive urbanisation of Funu landslide. Aerial and satellite images of Funu landslide for the period 1947 until 2018. 1947, 1959 and 1974 are derived from historical aerial images conserved at the RMCA. 2001 is an Ikonos satellite orthomosaic and 2013 and 2018 are very-high resolution Pléiades orthomosaics. These images were used in the evaluation of the changes in landslide motion and urban fabric over the last 70 years. Figure from Dille et al. (2022, manuscript in supplementary material).

For Bujumbura, with, as one of the key data sources, the use of the historical photographs from 1957-1959, 1970's and 1980's, we inventoried > 1200 landslides and tens of large gully systems (Figure 31). This allowed to show that more than 20% of the hillslopes are affected by these processes. The landslides are mostly concentrated in the rejuvenated landscapes, i.e. where a more recent river incision is reshaping the hillslopes. The recent landslides, i.e. those that have occurred since the 1950's, are mostly shallow and triggered by rainfall. The old landslides are larger, deep-seated and in majority no active. The variety of these processes (size, shapes, types) indicates that they witness various causes and triggers that have played a role over a long-time frame. The gully systems, sometimes affected by large landslide processes, are developed is loose lithologies. The fact that these features appear much less developed on the historical photographs, attest the role of urbanization on their occurrence. Further details can be found in Kubwimana et al. (2021, manuscript in supplementary material).

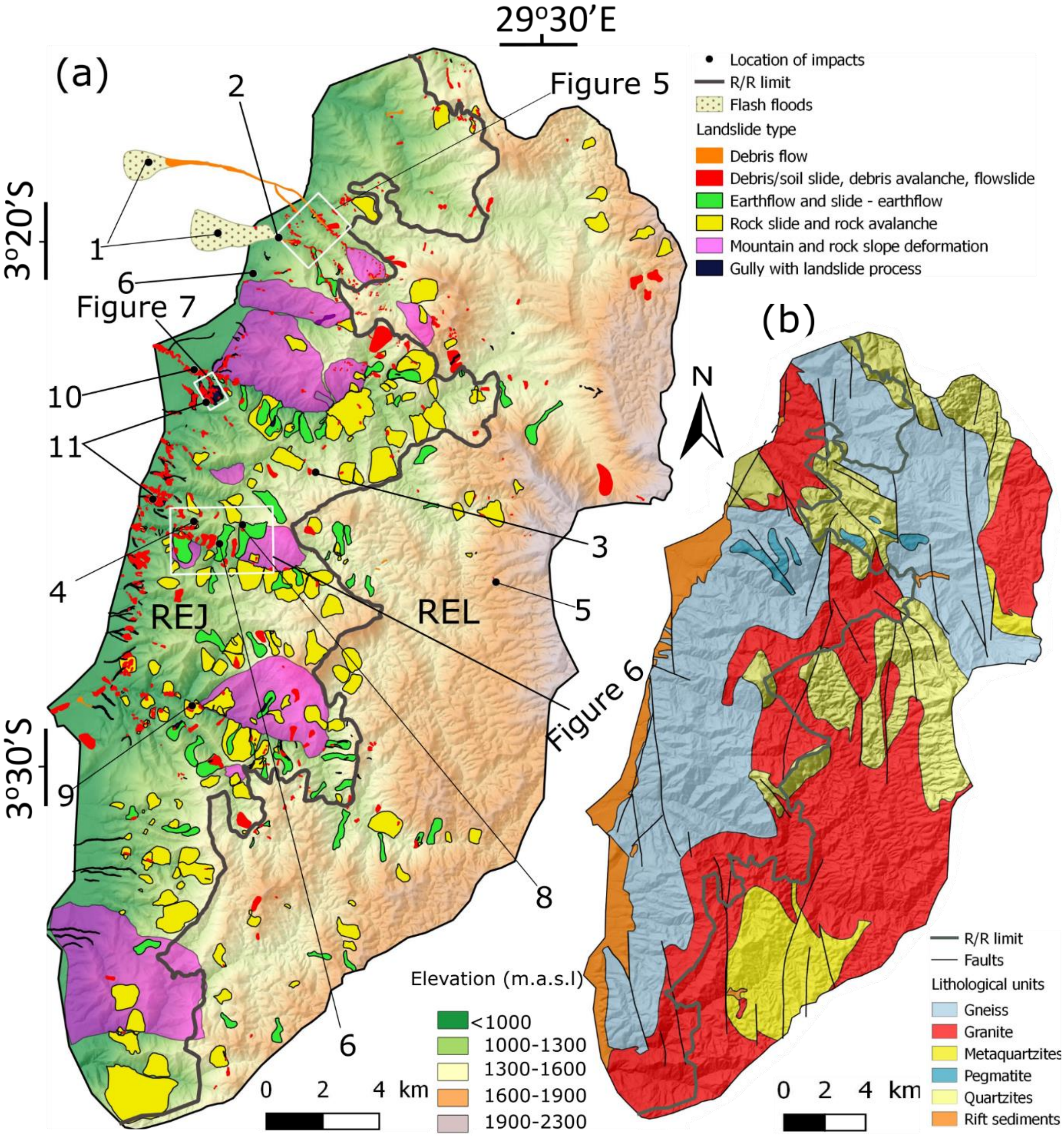


Figure 31. (a) Map of the location of the landslides inventoried in the area by type. The "R/R limit" line shows the position of the contact between the rejuvenated (west) and the relict (east) landscapes (REJ and REL)—note the difference in landslide density. (b) Lithological units and active faults for the study area (after Laghmouch et al., 2018b). Figure from Kubwimana et al. (2021, manuscript in supplementary material).

4.5. Societal dynamics and LULC modelling (WP6 & 8)

<u>At the regional level:</u>

Since the 1950's, the societal dynamics have been illustrated by several phases of spatial distribution variations undergone by the population of the region. These societal dynamics that are expected to have trends have had significant implications for the land use / land cover of the study area, and particularly for the preservation of the primary rainforest (Figure 32). By comparing these population dynamics to the historical evolution of forest cover (derived from the forest product obtained in Section 4.4), we observed that the forest cover extent in Rwanda and Burundi remained more or less stable in the past 60 years, despite a doubling of the population. Contrarily, the primary forest in the DR Congo has declined sharply, especially during the nineties. This sharp decline started at a time where the Congolese countryside was severely disrupted by the influx of Rwandan refugees. At the same time, the international demand for 3T minerals (tin, tantalum, tungsten), a commodity abundantly present in the eastern DR Congo, grew considerably. In response, mining activity in the region increased rapidly. The development of mining sites is expected to have a low direct impact on the forest cover, but the associated construction of roads and settlements facilitated access to the primary forest, making it more vulnerable to smallholder clearing and fuelwood extraction. For more details, see Depicker et al. (2021, manuscript in supplementary material).

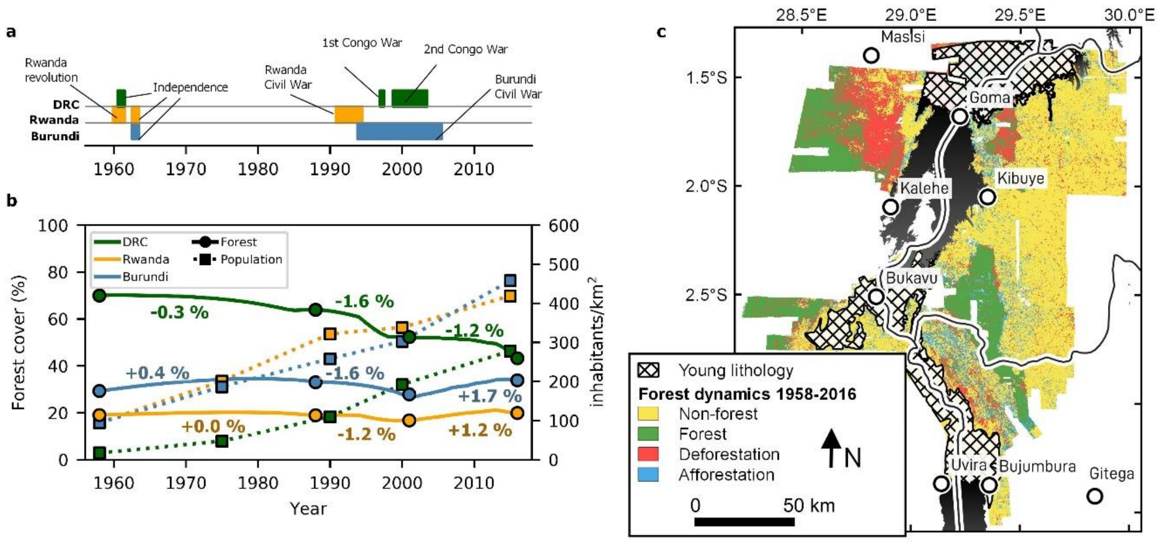


Figure 32. Conflicts, forest dynamics and demography in the Kivu Rift. a, Timeline of the major conflicts in the Kivu Rift. b, The forest-cover and population trends (http://data.europa.eu/89h/jrc-ghsl-ghs_pop_gpw4_globe_r2015a) The values indicate the mean annual forest-cover change. The annual forest-cover changes between four observations (1958, 1988, 2001 and 2016) are reconstructed by means of annual change estimates (how much land is deforested and afforested every year?) and deforestation and afforestation likelihood models (where will deforestation/afforestation happen first?). c, Forest-cover dynamics between 1958 and 2016 (this derived from forest cover reconstruction presented in Section 4.4). Figure from Depicker et al. (2021b, manuscript in supplementary material).

In general, the deforestation is expected to have increased the landslide hazard (where and how often will landsides occur) and thus the risk as well (how many people are killed by landslides). The reconstruction of the historical landslide hazard in the region is a complex exercise that is conducted in three consecutive steps: (i) the reconstruction of the annual forest cover changes between 1958 and 2016, (ii) the reconstruction of the annual landslide susceptibility influenced by those forest cover changes, and (iii) the conversion of susceptibility into landslide hazard. Steps (ii) and (iii) are derived from outputs from Section 4.5. For more details, see Depicker et al. (2021; manuscript in supplementary material).

A summary of the method is given here:

- The annual forest cover changes were reconstructed by means of a cellular automaton. This model relies on two variables: a deforestation/afforestation susceptibility model and a deforestation/afforestation rate. At a given year, the susceptibility model indicates which pixels of the forest map are most likely to be deforested/afforested, and the rate indicates how many pixels need to be deforested/afforested.
- Using contemporary landslide and deforestation data (for the period 2001-2016, see Depicker et al. (2021a) and section 4.5), we developed a shallow landslide susceptibility model that depends, among other predictors, on a dynamic forest cover variable. We distinguished 5 forest cover classes: forest and non-forest in rejuvenated landscapes, forest and non-forest in relict landscapes, and areas that were deforested < 15 years ago. Using the reconstructed annual forest cover evolution as a guideline, we can derive the dynamic forest cover variable and thus landslide susceptibility for each year between 1958 and 2016
- We calibrated the relationship between landslide susceptibility and hazard, whereby the latter is expressed as the affected area per km^2 per year. Although this relationship is valid for contemporary data, we assumed it can be extrapolated to the entire period 1958-2016.

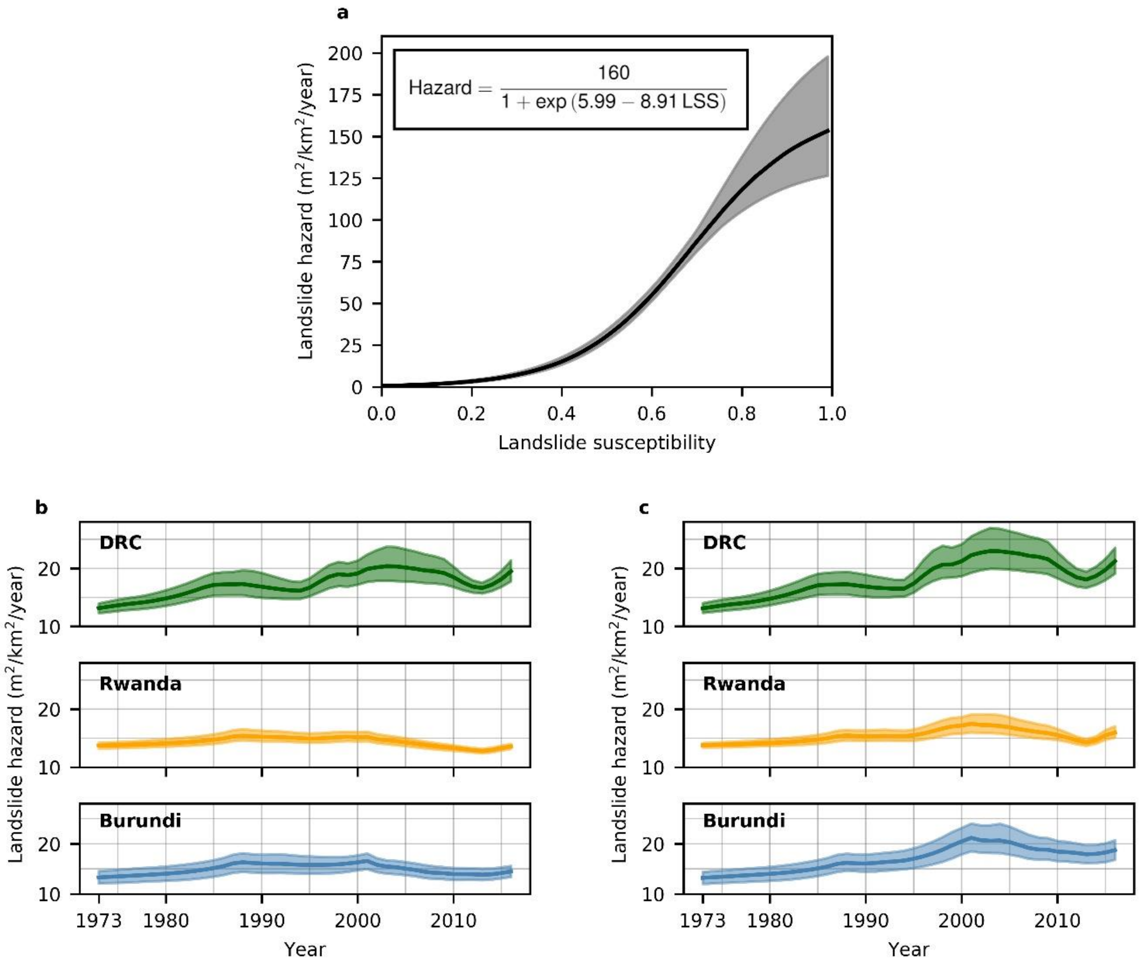


Figure 33. Landslide hazard trends in the Kivu Rift and the link with landslide susceptibility. a, Nonlinear relationship between landslide susceptibility and landslide hazard. b, Landslide hazard trends when we assume there is no landslide response to deforestation in new forests. c, Landslide hazard trends in the Kivu Rift when we assume the landslide response to deforestation is the same for new and primary forests. The solid lines in all panels indicate the median landslide hazard estimates, while the shaded areas indicate the 80% confidence intervals, which are calculated by applying Efron's bootstrap to the susceptibility model. Figure from Depicker et al. (2021b, manuscript in supplementary material).

The reconstruction shows that there had been a peak in landslide hazard in 2001 (Figure 33). Moreover, the hazard was highest in the eastern DR Congo, which linked to the higher deforestation rates. However, a high hazard does not necessarily reflect a high risk: the occurrence of landslides only becomes problematic when assets are exposed. Hence, to calculate the risk (Figure 34), we multiplied the spatially explicit hazard maps with population density grids provided for the epochs 1975, 1990, 2000, and 2015. We observed large differences in shallow landslide risk between, on the one hand, the DR Congo, and on the other hand, Rwanda and Burundi. To some extent, the risk is higher in the DR Congo because of the widespread deforestation. Yet, differences in risk persist even after subtracting the effect of forest cover changes. Hence, the risk in the DR Congo is also higher due to the location of the population in more hazardous terrain. Reflecting back to the societal dynamics in the region, we speculate that people migrated to such terrain due to land scarcity (especially after the influx of Rwandan refugees in 1994) and mining opportunities (Figure 35). In conclusion, our analysis demonstrates how the legacy of environmental and societal changes cannot be neglected in contemporary landslide risk assessments. For more details, see Depicker et al. (2021b, manuscript in supplementary material).

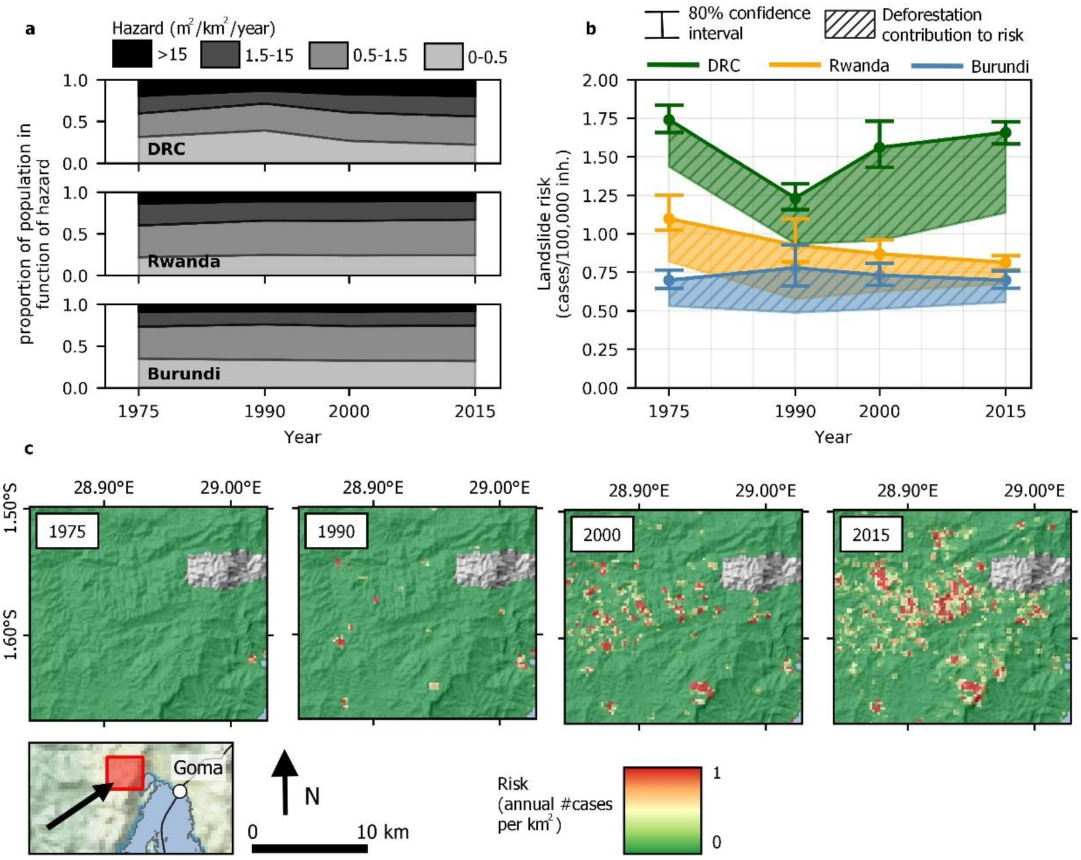


Figure 34. Landslide exposure and risk in the Kivu Rift. a, Exposure of the population to landslide hazard. b, Landslide risk trends and the impact of deforestation. c, Spatially explicit landslide risk assessment in four periods south of Masisi and west of Goma. For these risk maps, we presented the risk in a spatially explicit way (the number of cases per km2 per year) and improved the visual representation by decreasing the raster resolution by a factor of 10, retaining the maximal value of aggregated pixels. The average risk in this location in 2015 is 5.7 cases per 100,000 inhabitants, more than three times higher than the average risk in the studied part of the DR Congo. Figure from Depicker et al., 2021b (manuscript in supplementary material).

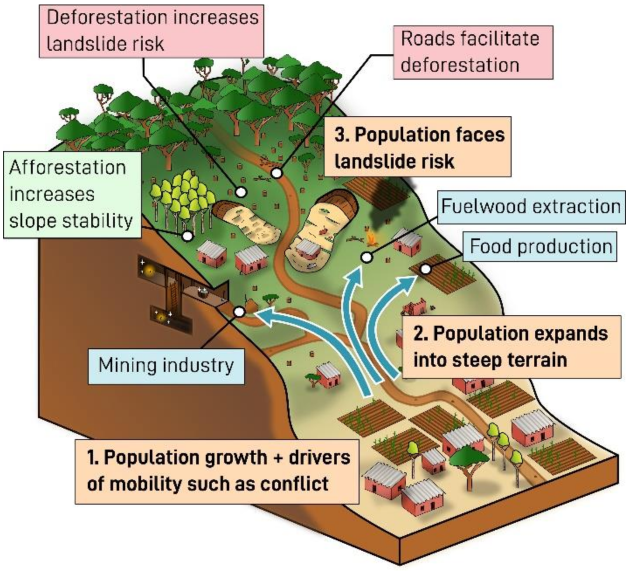


Figure 35. Conceptual overview of the key processes affecting shallow landslide risk in the Kivu Rift. The orange boxes represent the trajectory of the population. The blue boxes show the pull factors that attract people to steep terrain. The red boxes indicate human disturbances that directly or indirectly exacerbate the landslide risk, while the green box represents interactions that reduce the landslide risk. Figure from Depicker et al. (2021b, manuscript in supplementary material).

A the city level:

For each of the three studied city, we identified drivers underlying the observed changes using a range of secondary sources of information, as well as interviews, personal interactions, and extensive field experience. First, we explored secondary sources of information to adduce evidence of the driving factors and relate them to the observed growth patterns of the three cities. Moreover, since 2012, we have been interacting with multiple stakeholders (civil protection, city authorities, district leaders, provincial governors), academics and researchers. Almost 200 interviews were conducted with many of these key informants from various institutions, who either study the evolution of their city or work on related topics that provide them with a deep knowledge of their urban area. In addition, we jointly coordinated several socio-economic, demographic, and environmental surveys, with scientists from local institutions and teams of surveyors, which gave us the opportunity to deepen our field knowledge of each studied city. Details of the interviews are provided in Table S4 – Table S6 in Mboga et al. (in review, manuscript in supplementary material).

To structure the findings from secondary sources and interviews, we use an adjusted version of the conceptual model of manifestations and underlying drivers (Figure 36), which has been introduced to study agricultural changes before (van Vliet et al., 2015).

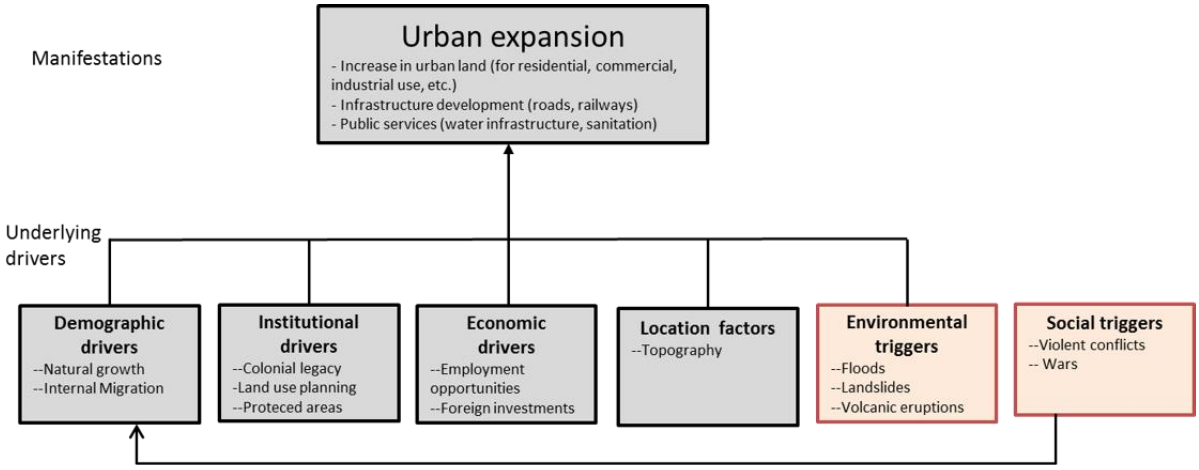


Figure 36. Conceptual framework of manifestation and underlying drivers of urban growth in Central Africa. Trigger events are indicated in red as they are the focus of this study. Figure from Mboga et al. (in review, manuscript in supplementary material).

Urban growth patterns: Across the three cities, the population growth rate was high in the period that followed independence (7.6% per year in Bukavu, 10.3% in Goma and 7.2% in Bujumbura), and subsequently decreased to 5% per year in the period 1975-1990 (Tables S8 in Mboga et al., in review, manuscript in supplementary material). This trend changed again in the decade between 1990 and 2000 as the population growth rate increased to above 5%. Between 2000-2010, the population growth rate of Bujumbura dropped to 2%, while the rate for Goma slightly decreased to 8.5%. On the other hand, the population growth rate of Bukavu increased to 8.5%. Although the percentages differ between time periods and between cities, these are all rather large compound growth rates, reflecting a more-or-less exponential increase in population (Fig 6). Consistently, the largest absolute increase in both population and built-up land took place after 1990. Population increased at a higher rate than built up area from the 1975 to 2010 in Goma, and from 1990 to 2020 in Bukavu (Table S8 in Mboga et al., in review, manuscript in supplementary material). In Bujumbura, this population growth exceeded the increase in built-up land between 1959-1975 as well as 1990-2001 (Table S8 in Mboga et al., in review, manuscript in supplementary material). Across the three cities, edge-expansion constituted the dominant pattern of built-up area growth, while Goma and Bujumbura also have significant amounts of infill development (Figure 37). Bujumbura is the only city where the share of outlying development exceeds 10% in any given period. Across the entire study period, built-up area in Bukavu increased slower than in Goma and Bujumbura, both in absolute terms and on a per-person basis. This difference started at around 1990, as the three cities were growing at a comparable rate before.

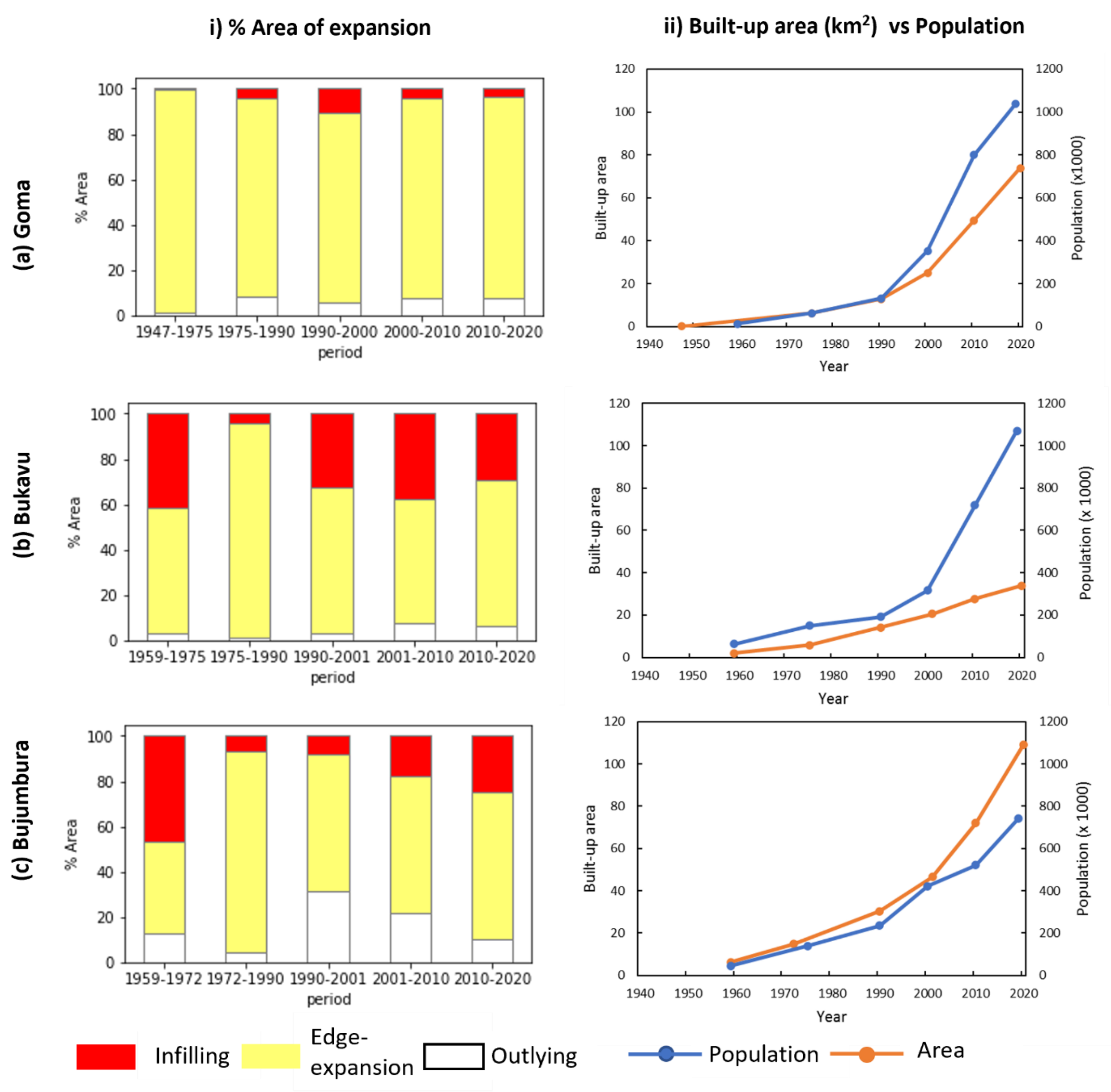


Figure 37. Built-up expansion patterns, total built-up land, and population numbers for (a) Goma, (b) Bukavu, and (c) Bujumbura during the entire study period. See supplementary S1.7 for a description of the population data and sources). Figure from Mboga et al. (in review, manuscript in supplementary material).

Drivers of urban growth: Overall, our study shows that both demographic dynamics and social triggers such as violent conflicts and wars were positively related to urban expansion. Second, as population pressure increased, constraining effects of natural environment such as relief and risks of natural hazards weakened, leading to urban development in less suitable areas (Figure 38). Table II provides an overview of the drivers of urban growth for the three cities. These results demonstrate the challenges that cities face towards sustainable urban development and highlight the need for planning and policy making to guide this process.

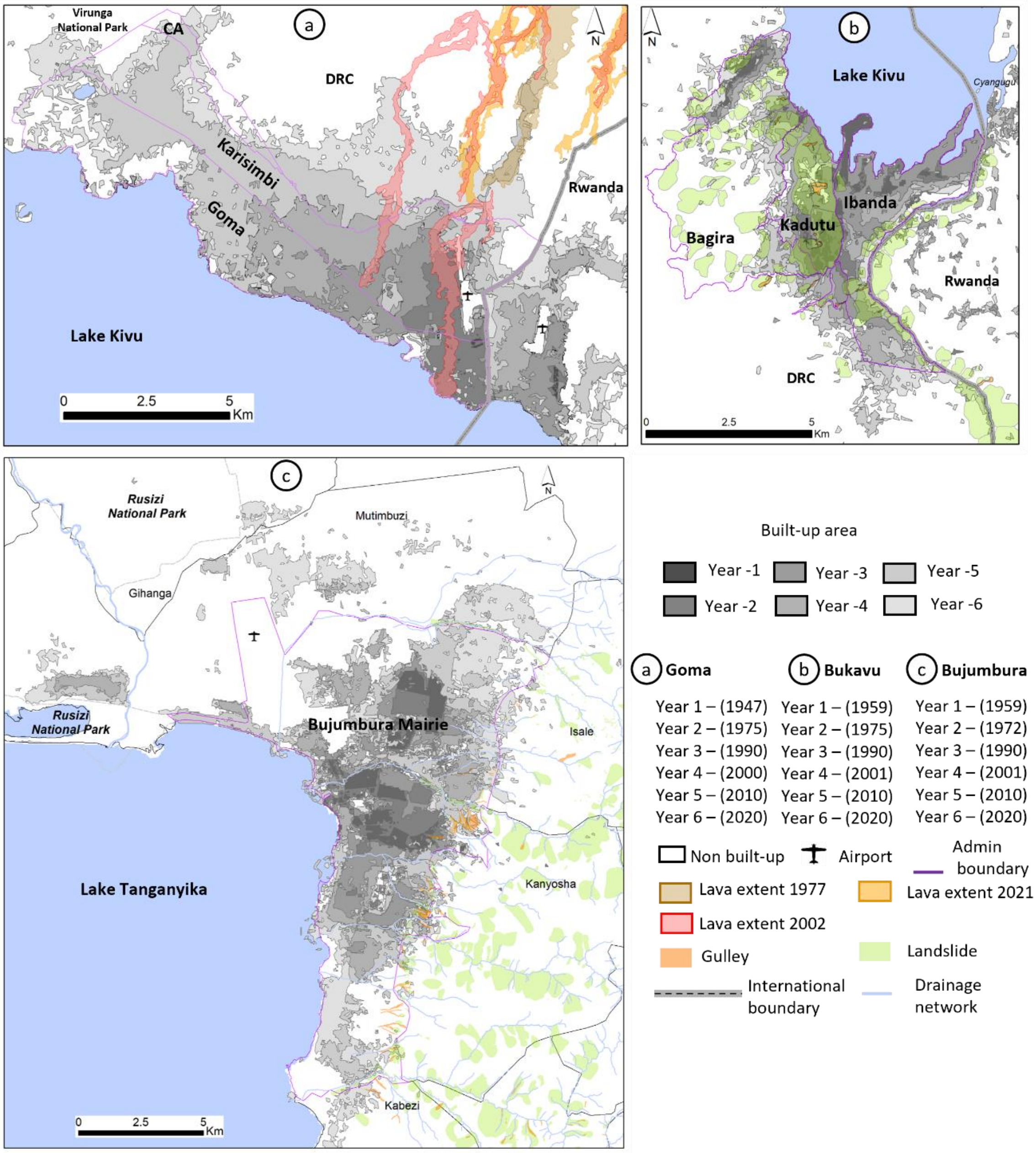


Figure 38. Natural hazards with respect to multi-temporal built-up area maps of the study area. In a) the lava extents are shown for the volcanic eruption of Mt. Nyiragongo for the years 1977, 2002 and 2021. In b) Bukavu, location of pre-urban landslides and gullies are presented. A detailed typology of landslides and gullies in Bukavu is described in Dewitte et al. (2021, manuscript in supplementary material). In c) the location of landslides and gullies are presented with a detailed typology in Kubwimana et al. (2021, manuscript in supplementary material). In a) Goma, CA represents contested area between the city authorities and traditional authorities. Figure from Mboga et al. (in review, manuscript in supplementary material).

Table II. Overview of drivers of urban change in the three cities. Table from Mboga et al. (in review, manuscript in supplementary material).

Drivers	Goma	Bukavu	Bujumbura
Institutional driver	-Colonial legacy influences location of urban center and creates fragmented built-up areas before independence (CEC). -Administrative capital of the North Kivu province from 1988. -Local administration enforces boundaries of the Virunga national park, inhibiting the extension of the city westwards. -Border with Rwanda prevents the expansion towards the East.	-Colonial legacy influences location of urban centers and creates fragmented built-up areas before independence (CEC). -Administrative capital of the Kivu province immediately after independence, and of the South Kivu province since 1988.	-Colonial legacy influences location of urban centers and creates a fragmented built-up area before independence (CEC). -Political capital of the country until 2018; since then, it remains the economic capital.
Demographic drivers	-Increase in migrants after independence. -Massive refugees influx following the genocide against the Tutsis in Rwanda. -Urban-rural migration due to recurrent violent conflict. -High natural population growth.	-Increase in migrants after independence. -Massive refugees influx following the genocide against the Tutsis in Rwanda. -Urban-rural migration due to recurrent insecurity. -High natural population growth.	-Increase in migrants after independence. -Urban-rural migration due to recurrent insecurity. -High natural population growth.
Economic drivers	-The tourist attraction initiates the development of the built-up area in the early days. -Availability of jobs attracted migrants after independence. -Foreign investments through international humanitarian organizations promote development encouraging local investments. -Majority of the population depends on the informal economy.	-Availability of jobs attracted migrants after independence. -Foreign investments through international humanitarian organizations promote development encouraging local investments. -Majority of the population depends on the informal economy.	-Availability of jobs attracted migrants after independence. -Gateway of the Belgian Colonial Empire to the Indian Ocean. -Bujumbura was capital of the country attracting international organizations.
Location effects	-Volcanic soils are fertile, attracting new inhabitants. -Westward growth encouraged by accessibility due to the road to Sake. -The lake Kivu, the PNVi and the boundary with Rwanda constrain the expansion of the city.	-Hilly terrains limit the accessibility of more remote parts of the city dampening its growth. -Lake Kivu acts as a natural inhibitor to expansion of the built-up area northwards.	-Town originally developed farther from the shore of Lake Tanganyika, due to risk of lake flooding. -Lake Tanganyika acts as a natural inhibitor to expansion of the built-up area westwards.
Social triggers	-Recurrent violent conflict leading to a large influx of people from the surroundings rural areas.	- Recurrent insecurity leading to a large influx of people from the surroundings rural areas.	-Resettlement of internally displaced people causes a southward expansion
Environmental trigger events	-2002 volcanic eruption destroyed 10% of the city, but the area was rebuilt.	-Landslides and gullying destroyed buildings and roads, but people still settle in these areas nonetheless	-Landslides and gullying threaten buildings and roads, but people settle in these areas nonetheless -Floods from the lake and the rivers regularly affect several districts displacing people, and the abandoned areas are commonly resettled

5 CONCLUSION AND RECOMMENDATIONS

The need to preserve and valorise a unique collection

Through its activities, PAStECA has demonstrated the scientific added value of the use historical aerial photographs to address key environmental change related issues. More specifically, with a relatively narrow focus on geo-hydrological hazards, deforestation and population dynamics in a rather small region of Africa, PAStECA has produced unprecedented outcomes as highlighted for example with the work published in Nature Sustainability.

Besides these scientific achievements on the understanding of the environment, PAStECA also generated scientific achievements oriented toward digital technologies for scanning and georeferencing the archives, which, combined to new machine learning methods, allowed to extract robust information from the paper-based historical documents.

PAStECA demonstrates that with rather limited means the preservation and the valorisation of historical aerial photographs is possible. However, PAStECA also shows that many of these photographs are deteriorating, therefore highlighting the urgent need to upscale such a work at the level the whole collection. In PAStECA about 6000 photographs have been processed while the RMCA's collection is > 370,000. Without an urgent priority given to the preservation of these archives through a digitization effort, we face the risk of losing unique information of the past environmental conditions of a region of Africa with important environmental and societal challenges (for example, biodiversity, climate, mineral resources, agriculture). But also, the digitization and the associated inventorying and archiving processes are the only way to make that scientific patrimony available to a larger scientific community dealing with global issues (deforestation, environmental and climates changes… Poor attention has been given to the supposedly twin collections of aerial photographs whose some remains can be found at institution in DR Congo and Burundi (in Rwanda everything has disappeared); this underlines the necessity for rescuing the RMCA collection before it is too late. Central Africa is clearly spotted as one of the regions on the world where the dearth of data is the most problematic (IPCC, 2021).

What can be said from the environment-related outputs of PAStECA?

The goal of PAStECA is the understanding of the changing environment through the valorisation of archive documents. Its goal is not to directly support decision making. However, it is important for policy makers (and the society at large) to know how these changes of the environment already impacted and/or will likely affect earth surface processes and hazards, which, in turn, may have impacts on humans. The research outputs of the project show some potential to be used as awareness raising support for policy makers. In addition, several of our additional research activities directly support local researchers and institutions.

At the regional level, the model proposed by Depicker et al. (2021b) shows a large spatial and temporal variation in landslide risk that is highly influenced by forest cover, demographic shifts, and settlement patterns. The risk at a local level may be up to three times higher than the average risk at a regional scale. Generally, such a high local risk is related to the expansion of a rural population in steep terrain at the expense of forests. Landslide risk can in principle be reduced by setting up policies to raise awareness and understanding of the problem (Maes et al., 2017), both in farming and mining communities. However, it is even more important to reduce the incentives for the local population to settle in hazardous areas as it influences both hazard (through deforestation) and risk (through increased exposure). This goal can be achieved by, for instance, encouraging the use of permanent agricultural land in low-hazard areas instead of slash and burn agriculture (Meyfroidt and Lambin, 2011; Willemen et al., 2020). Such a policy requires investments to increase the productivity of croplands (Meyfroidt and Lambin, 2011). The extraction of fuelwood (and hence deforestation) from primary forest can also be reduced by using more efficient stoves and/or by replacing fuelwood with other energy sources where this is feasible (Vervisch et al., 2013). At the same time, forests planted in hazardous areas may not only reduce landslide risk but may also serve as a source of fuelwood (Vervisch et al., 2013). All these policies would reduce the loss of primary forest and can facilitate reforestation, thereby initiating a forest transition.

Our analysis demonstrates the complexity of interactions between shallow landslide hazard and forest dynamics, indicating that a regional assessment solely based on a direct causal linkage between net forest-cover change and landslide hazard would be incomplete. Thus, to assess the evolution of landslide risk, we show that it is important to apply a spatially explicit approach and to account for the legacy of environmental and societal changes over a multidecadal timespan. Considering our observation that deforestation, compared with afforestation, exerts a larger effect on susceptibility and thus hazard, even a net expansion of forest cover can be associated with an increase in landslide hazard. It is pivotal to account for the spatial patterns in deforestation to estimate its overall impact on hazard, as the absolute impact of deforestation depends on the pre-existing susceptibility conditions. Furthermore, the impact of deforestation on hazard is temporary, and knowledge of the timing of forest-cover changes is also essential to assess the temporal dynamics of the landslide hazard.

While our study focused on the past, some of the drivers we identified (deforestation, mining activity and population expansion in steep terrain (**Figure 35**) are expected to be of high relevance for the future development of the area, especially in the highlands of the Kivu region in the eastern DR Congo (55–58). This is what we demonstrated in PAStECA where we show that mining activities and road construction for example are responsible for an increase in landslide occurrence (Maki Mateso et al., 2021; Depicker et al., to be submitted). Local and national governments as well as organisations that are locally active should therefore account for these drivers when designing disaster-risk-reduction programs related to the region.

At the level of the cities, PAStECA put a spotlight on the role of Earth observation data to monitoring of urban development for these purposes. The results of this work highlight how population pressure led to urban development in areas prone to natural hazards, in the absence policies that prevent this (Michellier et al., 2016; Michellier et al., 2018). Moreover, our findings illustrate the relationship between urban development and violent conflict, showing the importance of urban areas for supporting refugees as well as the impact they subsequently have on the urban area.

Sustainable urban development requires increasing the prosperity of cities while restricting urban land consumption (Bakker et al., 2021). Yet, it is important to consider a baseline situation when analysing land consumption per person. All three cities analysed here have had periods where population increase exceeded the growth in built-up land. While this could be considered sustainable according to SDG 11.3.1 (UNSTATS, 2018), these developments are all related to overcrowding, often from a high influx of people which is difficult to manage and provide facilities for, including refugees and internally displaced people due to war and recurrent insecurity. This then implies that the cities get overcrowded, and if the administrative authorities are not able to match the provision of goods and services to the rate of population growth, then slum-like conditions arise. Therefore, we argue that population growth is not *per se* a relevant baseline for assessing the sustainability of rapidly growing cities in sub-Saharan Africa, and that planning and policy making needs to consider local conditions first and foremost.

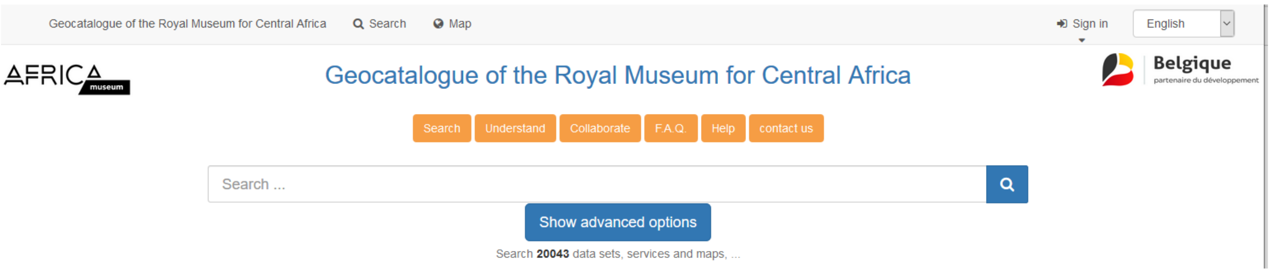
Based on our findings, we further suggest considering the role of trigger events to improve our understanding of urbanization in sub-Saharan Africa. With globalization, and increased global connectivity, changing population dynamics, emergent political class, the traditional drivers of urbanization are likely to change. Through a concerted effort to improve the standards of living in the rural areas, urbanization and urban growth in Africa could become manageable (Hope, 2008).

For the specific investigation of the Funu landslide in Bukavu, our findings show that urbanization can interfere with the natural behaviour of long-lived, deep-seated landslides. Such relationship is not surprising given how urbanization is known to affect slope hydrology (Lerner, 2002; Price, 2011; Fletcher et al., 2013) and how slope hydrology in turn regulates the motion of most slow-moving landslides (Carey et al., 2019; Iverson and Major, 1987; Hilley et al., 2004; Handwerger et al., 2013; Iverson, 2000; Dille et al., 2021). Large slow-moving landslides are known to sometimes abrupt transition from slow motion to catastrophic failure (Handwerger et al., 2019; Agliardi et al., 2020). Concerns are obviously higher when the landslide is embedded in a dense urban landscape. Avoidance of unstable slopes is usually not an option in developing countries, where informal urbanization generally outstrips any regulation (Satterthwaite et al., 2007). Mitigation strategies aiming at reducing water infiltration by a comprehensive management of all forms of surface water should be backed (Anderson and Holcombe, 2013). Those are complex to implement, especially for such large landslides, and while landsliding is not the primary concern of the urban population of Bukavu (primary concerns include access to potable water, sanitation, health, or education services and (food) security 26, Mboga et al., under review), community-based approaches (Holcombe et al., 2016; Anderson and Holcombe, 2013) should be promoted to prevent loss of life and infrastructure due to landsliding. As hillslopes of the world’s cities are being urbanized at accelerating paces (Schuster and Highland, 2007; Larsen, 2008), we believe that more studies are needed to improve our understanding of how anthropogenic activity influences surface processes and landscape evolution. This would ensure the valid evaluation of landslide hazard and optimization of mitigation strategies.

6. DISSEMINATION AND VALORISATION

Development of a web interface to identify available maps and archives

Most of the entire collection of maps available at RMCA have been scanned (more than 200,000 documents). Among those, several hundreds of documents are available for the PAStECA region. An overview of the data is provided through the Geocatalogue. https://geocatalogue.africamuseum.be/



Data valorisation and dissemination

- Project website: . http://pasteca.africamuseum.be/
  This channel for dissemination of project results and activities was regularly updated with results of field works, conference abstracts and scientific publications.

- Stakeholders:
  Contacts with local stakeholders have been maintained throughout the project, mostly through informal contacts during field campaigns done via this project or other activities led by RMCA (the members of the RMCA group involved in the project are totalizing, in average, going 10 times per year in the region expect during the COVID-19 pandemic travel restriction).

- CIRRiNA:
  Information centre on natural hazards and associated risks in Bukavu (DR Congo) developed in partnership with the RMCA teams of PAStECA and colleagues from the Université Officielle de Bukavu (UOB, DR Congo), within the framework of the HARISSA project. The Centre d'Information et de Recherche sur les Risques d'origine Naturelle (CIRRiNA) is first and foremost an information centre where the population of Bukavu can acquire a better knowledge of earthquakes, landslides and gully erosion, while learning how to better cope with these hazards (Figure 39). CIRRiNA also promotes research on natural hazards in the region through lecture series.

PAStECA was a key project whose scientific outputs support the information centre. The Figure 39b shows one of the 3D visual displayed at the CIRRiNA. This 3D landscape represents the study area of PAStECA. A beamer allows different thematic layers to be displayed. Here the photo shows the landslide susceptibility map produced within PAStECA (Figure 39c (center panel) and Figure 25, Depicker et al., 2020).

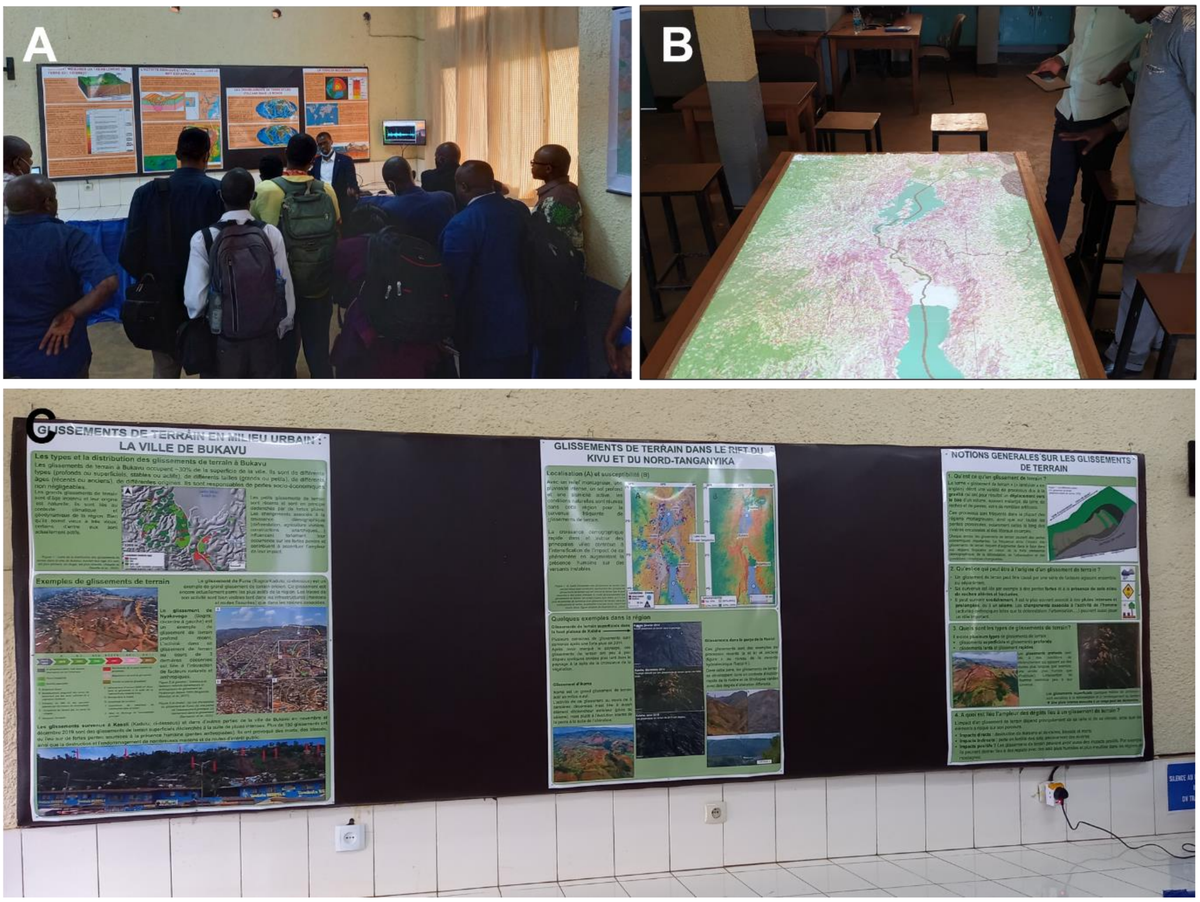


Figure 39. Overview of the CiRRIna in Bukavu (DR Congo). A) Inauguration of the centre with explanation about volcanic risks. A) 3D display at the study area of PAStECA with information from the project (namely, the landslide susceptibility map – Depicker et al., 2020 – Figure 25). C) Information on landslides hazard and risks.

Futher information (also video) can be found here:

- https://www.univofbukavu.org/2021/12/02/luob-lance-les-activites-du-centre-dinformation-et-recherche-sur-le-risques-naturels/
- https://georiska.africamuseum.be/en/launch_cirrina
- https://www.youtube.com/watch?v=7iViVLAFZI0

And also media coverage:

- https://juardc.info/2021/12/environnement/bukavu-un-centre-de-recherche-sur-les-catastrophes-naturelles-voit-le-jour-a-luob/
- https://www.radiomaendeleo.info/2021/11/30/environnement/sud-kivu-ouverture-dun-centre-des-recherches-sur-les-catastrophes-naturelles-a-luob/

- Geowebinars:
  These are online meeting organized by the GeoRiskA RMCA's team. Several times, researchers from PAStECA or using PAStECA data have been invited to present their research results at event. Organized every three weeks, these presentations are usually attended by 30 to 50 (mostly African) participants. The mailing list of the GEO-WEBINAR is made of more that 150 people, mostly from Africa. For more info: https://georiska.africamuseum.be/en/news

- Data availability:
  Key research ouputs from PAStECA are available online for the research community. They are listed here:

[1.] Dataset on the study of the Funu landslide (Bukavu, DRC) https://zenodo.org/record/7118267#.Y5j0NhZ7mUk, https://doi.org/10.5281/zenodo.7118267. Authors: Dille, A., Dewitte, O., Handwerger, A., d'Oreye, N., Derauw, D., Bamulezi Ganza, G., Ilombe Mawe, G., Michellier, C., Moeyersons, J., Monsieurs, E., Mugaruka Bibentyo, T., Samsonov, S., Smets, B., Kervyn, M., Kervyn, F., 2022.

[2.] Historical forest cover in the Kivu Rift (1958) https://zenodo.org/record/5027117#.YNTN1xZS-UI, https://doi.org/10.5281/zenodo.5027117. Authors: Depicker, A., Jacobs, L., Mboga, N., Smets, B., Van Rompaey, A., Lennert, M., Wolff, E., Kervyn, F., Michellier, C., Dewitte, O., Govers, G., 2021..

[3.] Shallow landslide inventory for 2000-2019 (eastern DRC, Rwanda, Burundi) https://zenodo.org/record/5027004#.YNTMZBZS-Uk https://doi.org/10.5281/zenodo.5027004. Authors: Depicker, A., Govers, G., Jacobs, L., Campforts, B., Uwihirwe, J., Dewitte, O., 2021.

[4.] Historical aerial photo pre-processing workflow (python scripts developed at the RMCA). https://github.com/GeoRiskA/historical_airphoto_preprocessing, https://zenodo.org/badge/latestdoi/366727725. Author: Smets, B., 2021.

[5.] Land cover mapping codes. https://github.com/Mboga/PASTECA_LC. Authors: Mboga, N., Grippa, T., 2021.

7. PUBLICATIONS

PAStECA authors are highlighted in bold.

Peer-reviewed publications

Publications with a "*" are those that were produced by lead authors directly financed by PAStECA. Publications with a "**" are those that were produced by lead authors directly involved in PAStECA, but not financially supported by the project.

Publications with a "***" are those that were produced by lead authors not directly involved in PAStECA, but with the support of PAStECA researchers and a direct contribution of PAStECA data.

[1.] ***Smets, B.**, **Dewitte, O.**, **Depicker, A.**, **Deijns, A.**, Dille A., **Lagmouch, M.**, **Michellier, C.**, Munganga, G., **Zwiener, T.**, **Kervyn, F.**, in preparation. Insights into the SfM photogrammetric processing of historical panchromatic aerial photographs without camera calibration information. ISPRS International Journal of Geo-Information. [I.F. 3.099]

[2.] ***Depicker, A.**, **Govers, G.**, **Jacobs, L.**, Vanmaercke, M., Uwihirwe, J., Campforts, B., Kubwimana, D., Maki Mateso, J.-C., Mugaruka Bibentyo, T., Nahimana, L., **Smets, B.**, **Dewitte, O.**, to be submitted. Landslide mobilization rates in a changing tropical environment: the North Tanganyika-Kivu Rift region, Africa. Science of the Total Environment. [I.F. 10.753]

[3.] ***Mugaruka Bibentyo, T., Dille, A., **Depicker, A.**, **Smets, B.**, Vanmaercke, M., Nzolang, C., Dewaele, S., **Dewitte, O.**, to be submitted. Landslides, bedrock incision and human-induced environmental changes in an extremely rapidly formed tropical river gorge. Geomorphology. [4.406]

[4.] ***Mboga, N.**, **Michellier, C.**, **Depicker, A.**, **Grippa, T.**, Georganos, S., **Vanhuysse, S.**, **Smets, B.**, Kubwimana, D., **Kervyn, F.**, **Dewitte, O.**, **Wolff, E.**, van Vliet, J., in review. Natural hazards and conflict dynamics as drivers of the long-term development of three cities in the East African Rift Valley. Land Use Policy. [I.F. 6.189]

[5.] ***Maki Mateseo, J.-C., Bielders, C., Monsieurs, E., **Depicker, A.**, **Smets, B.**, Tambala, T., Bagalwa Mateso, L., **Dewitte, O.**, accepted with minore revision. Characteristics and causes of natural and human-induced landslides in a tropical mountainous region: the Rift flank west of Lake Kivu (DR Congo). Natural Hazards and Earth System Sciences. [I.F. 4.580]

[6.] ***Dille, A., **Dewitte, O.**, Handwerger, A., d'Oreye, N., Derauw, D., Bamulezi Ganza, G., Ilombe Mawe, G., **Michellier, C.**, Moeyersons, J., Monsieurs, E., Mugaruka Bibentyo, T., Samsonov, S., **Smets, B.**, Kervyn, M., **Kervyn, F.**, 2022. Acceleration of a large deep-seated tropical landslide due to urbanization feedbacks. Nature Geoscience 15, 1048-1055. https://doi.org/10.1038/s41561-022-01073-3 [I.F. 21.531]

[7.] ***Deijns, A.**, **Dewitte, O.**, Thiery, W., d'Oreye, N., Malet, J.-P., **Kervyn, F.**, 2022. Timing landslide and flash flood events from SAR satellite: a new method illustrated in African cloud-covered tropical environments. Natural Hazards and Earth System Sciences 22, 3679 - 3700. https://doi.org/10.5194/nhess-22-3679-2022 [I.F. 4.580]

[8.] ****Dewitte, O.**, **Depicker A.**, Moeyersons, J., Dille A., 2022. Mass movements in tropical climates. In: Shroder, J.J.F. (Ed.), Treatise on Geomorphology, vol. 5. Elsevier, Academic Press, pp. 338–349. https://doi.org/10.1016/B978-0-12-818234-5.00118-8

[9.] ***Depicker, A.**, **Jacobs, L.**, **Mboga, N.**, **Smets, B.**, **Van Rompaey, A.**, **Lennert, M.**, **Wolff, E.**, **Kervyn, F.**, **Michellier, C.**, **Dewitte, O.**, **Govers, G.**, 2021. Historical dynamics of landslide risk from population and forest-cover changes in the Kivu Rift. Nature Sustainability 4, 965-974. https://doi.org/10.1038/s41893-021-00757-9 [I.F. 27.157]

[10.] ***Mboga, N.**, D'Aronco, S., **Grippa, T.**, Pelletier, C., Georganos, S., **Vanhuysse, S.**, **Wolff, E.**, **Smets, B.**, **Dewitte, O.**, **Lennert, M.**, Wegner, J.D., 2021. Domain adaptation for semantic segmentation of historical panchromatic orthomosaics in Central Africa. ISPRS International Journal of Geo-Information 10, 523. https://doi.org/10.3390/ijgi10080523 [I.F. 3.099].

[11.] ***Kubwimana, D., Ait Brahim, L., Nkurunziza, P., Dille, A., **Depicker, A.**, Nahimana, L., Abdelouafi, A., **Dewitte, O.**, 2021. Characteristics and distribution of landslides in the populated hillslopes of Bujumbura, Burundi. Geosciences 11, 259. https://doi.org/10.3390/geosciences11060259

[12.] ***Depicker, A.**, **Govers, G.**, **Jacobs, L.**, Campforts, B., Uwihirwe, J., **Dewitte, O.**, 2021. Interactions between deforestation, landscape rejuvenation, and shallow landslides in the North Tanganyika - Kivu Rift region, Africa. Earth Surface Dynamics 9, 445-462. https://doi.org/10.5194/esurf-9-445-2021 [I.F. 4.336]

[13.] ****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 18, 161-177. https://doi.org/10.1007/s10346-020-01452-0 [I.F. 6.153]

[14.] ***Mboga, N.**, **Grippa, T.**, Georganos, S., **Vanhuysse, S.**, **Smets, B.**, **Dewitte, O.**, **Wolff, E.**, **Lennert, M.**, 2020. Fully convolutional networks for land cover classification from historical panchromatic aerial photographs. ISPRS Journal of Photogrammetry and Remote Sensing 167, 385-395. https://doi.org/10.1016/j.isprsjprs.2020.07.005 [I.F. 8.979].

[15.] ***Depicker, A.**, **Jacobs, L.**, Delvaux, D., Havenith, H.-B., Maki Mateso, J.-C., **Govers, G.**, **Dewitte, O.**, 2020. The added value of a regional landslide susceptibility assessment: the western branch of the East African Rift. Geomorphology 353, 106886. https://doi.org/10.1016/j.geomorph.2019.106886 [I.F. 4.139]

[16.] ***Dille, A., **Kervyn, F.**, Mugaruka Bibentyo, T., Delvaux, D., Bamulezi Ganza, G., Ilombe Mawe, G., Kalikone Buzera, C., Safari Nakito, E., Moeyersons, J., Monsieurs, E., Nzolang, C., **Smets, B.**, Kervyn, M., **Dewitte, O.**, 2019. Causes and triggers of deep-seated hillslope instability in the tropics – insights from a 60-year record of Ikoma landslide (DR Congo). Geomorpholoy 345, 106835. https://doi.org/10.1016/j.geomorph.2019.106835 [I.F. 3.819]

[17.] ***Mboga, N.**, Georganos, S., **Grippa, T.**, **Lennert, M.**, **Vanhuysse, S.**, **Wolff, E.**, 2019. Fully Convolutional Networks and Geographic Object-Based Image Analysis for the Classification of VHR Imagery. Remote Sens. , 11, 597. https://doi.org/10.3390/rs11050597 [I.F. 4.118]

[18.] ***Monsieurs, E., **Dewitte, O.**, **Depicker, A.**, Demoulin, A., 2019. Towards a transferable antecedent rainfall – susceptibility threshold approach for landsliding. Water 11, 2202. https://doi.org/10.3390/w11112202 [I.F. 2.544]

[19.] ***Mboga, N.**, Georganos, S., **Grippa, T.**, **Lennert, M.**, **Vanhuysse, S.**, **Wolff, E.**, 2018. Fully convolutional networks for the classification of aerial VHR imagery". GEOBIA 2018- Geobia in a Changing World, 2018, pp. 1–12.

[20.] ***Smets B.**, **Michellier C.**, Syavulisembo A.M., Muganga G., d'Oreye N., **Kervyn F.**, 2018. Very high-resolution imaging of the city of Goma (North Kivu, D.R. Congo) using SfM-MVS photogrammetry. 2018 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 3370-3373. doi: 10.1109/IGARSS.2018.8517412.

PhD theses directly supported by PAStECA

2017 (10)-2021 (10) **Arthur Depicker** (Full-time PhD student – PAStECA project, Department of Earth and Environmental Sciences, KU Leuven, Belgium). "Landslide in a changing tropical environment: the North Tanganyika – Lake Kivu Rift region, Africa". Supervisors: Gerard Govers and Liesbet Jacobs (KU Leuven) and Olivier Dewitte (RMCA). PhD committee: Matthieu Kervyn (VUB), Matthias Vanmaercke (KU Leuven). Defended 22 October 2021.

2017 (11)-2021 (10) **Nicholus Mboga** (Full-time PhD student – PAStECA project, Laboratoire d'Analyse Géospatiale, ULB, Belgium). "Long-term mapping of urban areas using remote sensing - Application of deep learning using case-studies of data from Central Africa". Supervisors: Eléonere Wolff and Taïs Grippa (ULB). PhD committee: François Kervyn (RMCA), Anton Van Rompaey (KU Leuven). Defended 27 October 2021.

BSc, MSc, and PhD theses

Valorisation and additional work has been provided by the BSc, MSc and PhD students supervised by PAStECA members (underlined):

- **THESIS 1:** 2016 (10)-2021 (03) Antoine Dille (Full-time PhD student, Department of Earth Sciences, RMCA, and Department of Geography, VUB, Belgium). "Remote sensing of slow-moving landslides in the tropics: natural and anthropogenic controls". Supervisors: Olivier Dewitte (RMCA), François Kervyn (RMCA) and Matthieu Kervyn (VUB).
- **THESIS 2:** 2017 (10)- 2023 (02)present Jean-Claude Maki Mateso (Full-time PhD student, Earth and Life Institute, UCL, Belgium). "Interactions between landslides, land use and management. A case study on the rift flanks west of Lake Kivu". Supervisors: Olivier Dewitte (RMCA) and Charles Bielders (UCLouvain).
- **THESIS 3:** 2017-2018 Toussaint Mugaruka Bibentyo (Advanced master in Disaster and Risk Management, University of Liège, Belgium). "Landslide spatio-temporal distribution in a changing environment: focus on the Ruzizi gorges at the DR Congo – Rwanda border". Supervision by Olivier Dewitte with the support of Arthur Depicker and Benoît Smets.
- **THESIS 4:** 2018 (01)-2022 (04) Désiré Kubwimana (Full-time PhD student, Department of Geology, Université du Burundi, Burundi, Mohammed V University in Rabat, Morocco). "Mouvements de terrain dans les reliefs de Bujumbura (Burundi): apport des géosciences, inventaire, caractérisation et prédiction d'un aléa par les méthodes géostatistiques". Supervisors: Tarik Bahaj, Lahsen Ait Brahim (UM5) and Olivier Dewitte (RMCA).
- **THESIS 5:** Lore Steyaert (MSc. in Geography, VUB/KULeuven) : Feb – April 2018 : "Orthomosaic and digital photogrammetry – use of RMCA collections". Internship for the MSc. of Science in Geography (VUB – KU Leuven). RMCA supervisor: Benoît Smets.

- **THESIS 6:** 2018-2020 Laurent Vandervelde (MSc. in Sciences et gestion de l'environnement, ULB, Belgium). "Tracking ground deformations in an urban sprawling context: focus on the city of Bujumbura (DR Congo)". Supervision by Olivier Dewitte and Moritz Lennert, with the contribution of Benoît Smets and François Kervyn.
- **THESIS 7:** 2019 (10)-present Guy Ilombe Mawa (Full-time PhD student, Department of Geography, ULiège, Belgium). "Predicting the susceptibility, expansion rate and impacts of urban gullies in the D.R. Congo". Supervisors: Matthias Vanmaercke (ULiège) and Fils Makanzu Imwangana (UNIKIN). Co-supervisor: Olivier Dewitte (RMCA).
- **THESIS 8:** 2019 (10)-present Jean Nsabimana (Full-time PhD student, Department of Earth Sciences, RMCA, and Department of Geography, UNamur, Belgium). "Vulnerability to hydrologyical processes in an urban context: the city of Bujumbura (Burundi)". Supervisors: Caroline Michellier (RMCA), Sabine Henry (UNamur), PhD committee: Olivier Dewitte (RMCA), Aloys Ndayisenga (UB).
- **THESIS 09:** 2020-2021 Ellen Biesmans (MSc. in Geography, KU Leuven - VUB, Belgium). "Landslide path dependency in NW Rwanda". Supervision by Arthur Depicker, with the contribution of Olivier Dewitte.
- **THESIS 10:** 2020-2021 Ine Deroo (MSc. in Geography, KU Leuven - VUB, Belgium). "Landslides and terraces in NW Rwanda". Supervision by Arthur Depicker, with the contribution of Olivier Dewitte.

8. ACKNOWLEDGEMENTS

The PAStECA project would not have been possible without the collaboration and interactions with many partners. Therefore, we take this opportunity to acknowledge their contributions briefly. First of all, the PAStECA team would like to thank the member of the PAStECA follow-up committee for their insightful discussions and recommendation regarding this project. The follow-up committee consists of the following members: Frank Canters (Vrije Universiteit Brussel, Belgium), Fils Makanzu Imwangana (Université de Kinshasa, DR Congo), Augusta Marie Christine Umutoni (Lake Kivu Monitoring Programme, Rwanda), Geatan Sakindi (Lake Kivu Monitoring Programme Rwanda) and Jasper Van Vliet (Vrije Universiteit Amsterdam, the Netherlands). Although physical meetings could not be organized easily with everyone, the members of the follow-up committee were always available to provide an advice on the yearly reports, discuss intermediate results at conferences, or during field visits.

Second, we want to show our gratitude to the many colleagues who where involved in our research activities; many of them being associated as co-authors with the publications that results from PAStECA. A special thanks goes to the colleagues from the Université Officielle de Bukavu (DR Congo) whom collaborated with us to the setting up of the information center on natural hazards and associated risks (CIRRINA) on their campus. This information centre is a key achievement for the dissemination of the outputs of PAStECA.

Lastly, we want to acknowledge BELSPO for funding the PAStECA project. In addition, we want to acknowledge the STEREO III programme of BELSPO (MODUS project), FWO VLaanderen, and the Development Cooperation programme of the Royal Museum for Central Africa, which is supported directly by the Directorate-General Development Cooperation and Humanitarian Aid of Belgium (projects RA_S1_RGL_GEORISK and HARISSA) for providing additional funding that also contributed to help produce the scientific results presented in this report.

ANNEXES

Annex 1

Extra analyses based on PAStECA ouputs that were carried out with the support of additional projects):

1) Focus on the Kalehe region (Figure 1 and Figure 8b) and more generally on the mountains west of Lake Kivu

In this work, we use the historical photographs to further explore the role of land transformation on the occurrence of landslides. Compared to the forest cover dynamic analysis carried out in Section 4.4 (Depicker et al., 2021b, manuscript in supplementary material), this extra work extend over an extra region located between Bukavu and Kalehe (Figure 40). More specifically, we explore the impact of forest cover dynamics, roads and mining activities on the characteristics and causes of landslides. To do so, we compile a comprehensive multi-temporal inventory of 2730 landslides of different types that we group into five categories and that we analyze accordingly via frequency-area statistics, frequency ratio distribution and logistic regression susceptibility assessment. We find that natural factors contributing to the cause of recent (post 1950's) and old deep-seated landslides were either different or changed over time. Under similar topographic conditions, shallow landslides are more frequent, but of smaller size, in areas where deforestation has occurred since the 1950's. We attribute this size reduction to the decrease of regolith cohesion due to forest loss, which allows for a smaller minimum critical area for landsliding. In areas that were already deforested in 1950's, 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. Mining and road landslides 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 landslides over a multi-decadal period of observation. This work (Maki Mateso et al., 2021) is available in preprint here https://nhess.copernicus.org/preprints/nhess-2021-336/ and is about to be published. For more details, see Maki Mateso et al. (2021, manuscript in supplementary material).

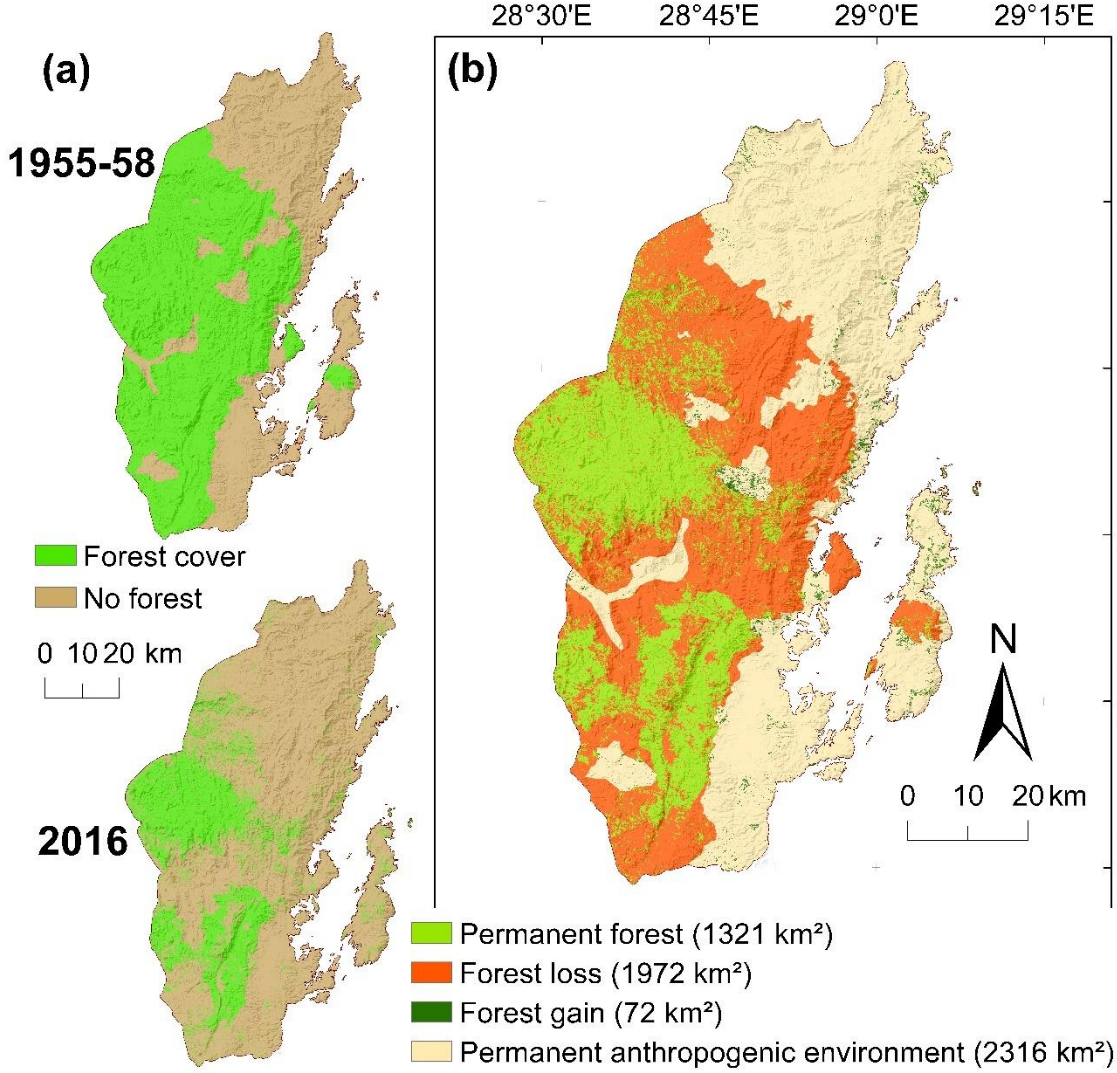


Figure 40. Forest cover dynamics over the last 60 years. (a) Forest cover in 1955-58 and 2016; (b) Areas of forest cover change between 1955-58 and 2016. Figure from Maki Mateso et al. (2021, manuscript in supplementary material).

2) Focus on the Ruzizi Gorge

Landslides are ubiquitous hillslope processes whose occurrence is controlled by natural changing topographic and lithologic conditions. Landslides are also influenced by human-induced landscape change. In this work, we use the historical photographs and the derived orthomosaic (Section 4.2, Depicker et al., 2021b) to investigate in detail the interplay between typically long-term natural and short-term natural or human-induced controls on landslides. We document these interactions in the Ruzizi Gorge (Figure 1), that is an exceptional geomorphological landmark whose origin is associated with the rerouting of > 7000 km² of drainage area from Lake Kivu during the Holocene. This bedrock river has also seen its landscape disturbed over the last decades by the development of the city of Bukavu. In addition to the historical aerial photographs, we combine careful field observations, satellite imagery and archive analysis to produce a multi-temporal inventory of 385 landslides and constrain their dynamics (Figure 41). We show that an extremely high incision rate (during the early stage of the formation of the gorge explains the space-time clustering of thousand-year-old large (up to 2 km²) landslides, independently from the lithological context. These landslides are currently mostly inactive and poorly eroded. Their deposit areas partly cover the riverbed, preventing channel incision. The landslides that occurred over the last 60 years are shallower slope failures of smaller size (up to 0.12 km²) and higher mobility. They tend to disappear rather quickly from the landscape (sometimes within a few years). Although land use changes certainly influence their occurrence, their distribution is primarily related to threshold slopes, lithology and the past large landslides. Overall, the sediment mobilization rates associated with these everyday landslides outpace significantly the extreme landslide erosion pulse associated with the gorge formation. This study provides insights on interactions and feedbacks around landslide processes in a unique environment, showing the importance of understanding the geomorphologic context in the assessment of a current hazard. For more details, see Mugaruka Bibentyo et al. (to be submitted, manuscript in supplementary material).

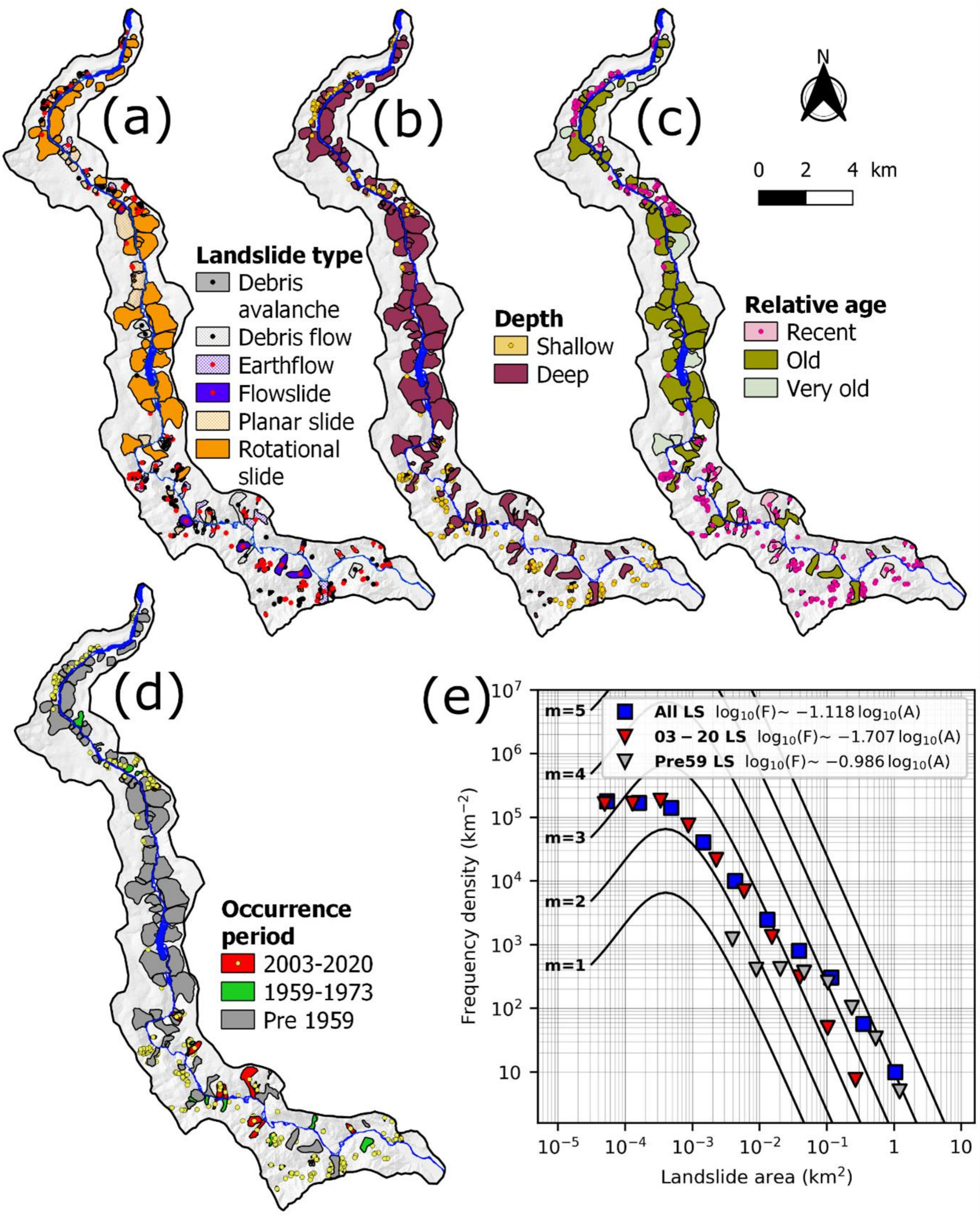


Figure 41. Landslide processes. (a, b, c, d) Landslide classified by type, depth, relative age, and occurrence period respectively. In order to be visible at the scale of the maps, the landslides <2000 m2 are symbolized with a dot. (e) Landslide frequency-area distributions for the whole inventory (All LS), the 2003-2020 landslides (03-20 LS), and the pre-1959 landslides (Pre59 LS). The black curves indicate the frequency-area distributions for inventories of different magnitudes of Malamud et al. (2004). Figure from Mugaruka Bibentyo et al. (to be submitted, manuscript in supplementary material).

Annex 2
Participation to conferences and workshops

Note: PAStECA authors are highlighted in bold.

2021

[1.] **Dewitte,O.**, **Deijns, A.**, **Depicker, A.**, Dille, A., Kanyiginya, V., Kubwimana, D., Maki Mateso, J.-C., Mugaruka Bibentyo, T., 2021. Landslide timing in a changing tropical environment: the North Tanganyika-Kivu Rift region, Africa. 5th World Landslide Forum, Kyoto, Japan, 2 – 9 November 2021 (Online-oral).

[2.] Mugaruka Bibentyo, T., Dille, A., **Depicker, A.**, Smets, B., Vanmaercke, M., Nzolang, C., Dewaele, S., **Dewitte, O.**, 2021. Landslides, river incision and environmental change: the Ruzizi gorge in the Kivu Rift. CRGM - Les IXème journées scientifiques - Les risques naturels : leur connaissance, impact environnemental et sociétal en RD. Congo, Kinshasa, DR Congo, 28-29 October 2021 (Oral).

[3.] Maki Mateso, J.-C., Bielders, C., Monsieurs, E., **Depicker, A.**, **Smets, B.**, Tambala, T., Bagalwa Mateso, L., **Dewitte, O.**, 2021. Characteristics, distribution and susceptibility of natural and human-induced landslides in a tropical mountainous region: the Rift flank west of Lake Kivu (DR Congo). CRGM - Les IXème journées scientifiques - Les risques naturels : leur connaissance, impact environnemental et sociétal en RD. Congo, Kinshasa, DR Congo, 28-29 October 2021 (Online-oral).

[4.] **Smets, B.**, Barrière, J., **Dewitte, O.**, **Deijns, A.**, Delhaye, L., **Depicker, A.**, Derauw, D., Dille, A., d'Oreye, N., Theys, N., **Zwiener, T.**, **Kervyn, F.**, 2021. Remote sensing of geo-hydrological hazards in Central Africa. 7th International Geologica Belgica Meeting 2021 “Geosciences Made in Belgium”, Tervuren, Belgium, 15 – 17 September 2021 (Poster).

[5.] **Dewitte, O.**, **Deijns, A.**, **Depicker, A.**, Dille, A., Kanyigina, V., Kubwimana, D., Maki Mateso, J.-C., Mugaruka Bibentyo, T., Sekajugo, J., 2021. Landslide timing in the changing environments of the North Tanganyika-Kivu Rift region, Africa. 7th International Geologica Belgica Meeting 2021 “Geosciences Made in Belgium”, Tervuren, Belgium, 15 – 17 September 2021 (Poster).

[6.] Maki Mateso, J.-C., Bielders, C., Monsieurs, E., **Depicker, A.**, **Smets, B.**, Tambala, T., Bagalwa Mateso, L., **Dewitte, O.**, 2021. Characteristics, distribution and susceptibility of natural and human-induced landslides in a tropical mountainous region: the Rift flank west of Lake Kivu (DR Congo). EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-13380, https://doi.org/10.5194/egusphere-egu21-13380, Vienna, Austria, 19 – 30 April 2021 (Online-oral).

[7.] **Depicker, A.**, **Jacobs, L.**, **Mboga, N.**, **Smets, B.**, **Van Rompaey, A.**, **Lennert, M.**, **Kervyn, F.**, **Michellier, C.**, **Dewitte, O.**, **Govers, G.**, 2021. Landslide risk trends in the Kivu Rift and the impact of environmental and societal dynamics. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-8927, https://doi.org/10.5194/egusphere-egu21-8927, Vienna, Austria, 19 – 30 April 2021 (Online-oral).

[8.] Mugaruka Bibentyo, T., Dille, A., **Depicker, A.**, **Smets, B.**, Vanmaercke, M., Nzolang, C., Dewaele, S., **Dewitte, O.**, 2021. Landslides, river incision and environmental change: the Ruzizi gorge in the Kivu Rift. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-11067, https://doi.org/10.5194/egusphere-egu21-11067, Vienna, Austria, 19 – 30 April 2021 (Online-oral).

[9.] **Mboga, N.**, **Grippa, T.**, **Georganos, S.**, **Vanhuysse, S.**, **Smets, B.**, **Dewitte, O.**, **Wolff, E.**, **Lennert, M.**, 2021. Fully convolutional networks for land cover classification from historical panchromatic aerial photographs. EARSel Joint Workshop 2020, Liège, Belgium, 30 March 30 – 01 April 2021 (Online-oral)

2020

[10.] **Depicker, A.**, **Jacobs, L.**, **Mboga, N.**, **Smets, B.**, **Van Rompaey, A.**, **Lennert, M.**, **Kervyn, F.**, **Michellier, C.**, **Dewitte, O.**, **Govers, G.**, 2020. Landslide risk in the Kivu Rift: the legacy of a political and environmental crisis. Young Researchers' Overseas Day - Royal Academy for Overseas Sciences, Brussels, 15 December 2020. (Online-oral).

[11.] Maki Mateseo, J.-C., Bielders, C., Monsieurs, E., **Depicker, A.**, **Smets, B.**, Tambala, T., Bagalwa Mateso, L., **Dewitte, O.**, 2020. Characteristics and distribution of natural and human-induced landslides in the Rift flank west of Lake Kivu (DR Congo). Young Researchers' Overseas Day - Royal Academy for Overseas Sciences, Brussels, 15 December 2020 (Online-poster).

[12.] **Depicker, A.**, **Govers, G.**, **Jacobs, L.**, Campforts, B., Uwihirwe, J., **Dewitte, O.**, 2020. Shallow Landslides in the North Tanganyika-Kivu Rift Region: Interactions Between Deforestation and Landscape Rejuvenation. Abstract EP007-07, AGU Fall Meeting, San Francisco, USA, 1-17 December 2020 (Online-oral).

[13.] Dille, A., **Kervyn, F.**, Kervyn, M., **Dewitte, O.**, 2020. Dynamics of deep-seated landslides in the tropics: natural and anthropogenic controls. Abstract NH031-03, AGU Fall Meeting, San Francisco, USA, 1-17 December 2020 (Online-oral).

[14.] Maki Mateseo, J.-C., Bielders, C., Monsieurs, E., **Depicker, A.**, **Smets, B.**, Tambala, T., Bagalwa Mateso, L., **Dewitte, O.**, 2020. Characteristics and distribution of natural and human-induced landslides in the Rift flank west of Lake Kivu (DR Congo). RMCA PhD day, Tervuren, Belgium, 20 November 2020 (Online-oral).

[15.] **Depicker, A.**, **Dewitte, O.**, **Jacobs, L.**, **Govers, G.**, 2020. Landslides in a changing environment. RMCA PhD day, Tervuren, Belgium, 20 November 2020 (Online-oral).

[16.] **Depicker, A.**, **Govers, G.**, **Jacobs, L.**, Campforts, B., Uwihirwe, J., **Dewitte, O.**, 2020. Landslide frequency in the Kivu Rift: impact of landscape evolution and deforestation. Geophysical Research Abstracts 22, EGU2020- 17974, EGU General Assembly, Vienna, Austria, 04 – 08 May 2020 (Online).

[17.] **Depicker, A.**, **Govers, G.**, **Jacobs, L.**, Campforts, B., Uwihirwe, J., **Dewitte, O.**, 2020. Deforestation reduces the impact of rifting on landslides. Workshop “Slope processes in challenging environments - tools, approaches and perspectives”, Tervuren, Belgium, 11 March 2020 (Poster).

2019

[18.] Dille, A., **Kervyn, F.**, **Smets, B.**, Monsieurs, E., d’Oreye, N., Kervyn, M., **Dewitte, O.**, 2019. Dynamics of slow-moving deep-seated landslides in the tropics: insights from combined analysis of long InSAR time series and ground-based measurements. Innsbruck Summer School of Alpine Research “Close range sensing techniques in Alpine terrain”, Innsbruck, Austria, 16 – 22 June 2019 (Poster).

[19.] Dille, A., **Dewitte, O.**, Derauw, D., Libert, L., Monsieurs, E., **Smets, B.**, Kervyn, M., d’Oreye, N., **Kervyn, F.**, 2019. Kinematics of deep-seated landslides in a tropical urban environment: insight from combined analysis of long InSAR time series and ground-based measurements. ESA Living Planet Symposium 2019, Milan, Italy, 13-17 May 2019 (Oral).

[20.] **Depicker, A.**, **Jacobs, L.**, Maki Mateso, J.-C., Delvaux, D., Havenith, H.-B., **Govers, G.**, **Dewitte, O.**, 2019. Aadded value of regional versus global landslide susceptibility: western branch of the East African Rift. Geophysical Research Abstracts 21, EGU2019-18367, EGU General Assembly, Vienna, Austria, 07 - 12 April 2019 (Oral).

[21.] Dille, A., **Kervyn, F.**, Mugaruka Bibentyo, T., Delvaux, D., Ganza Bamulezi, G., Ilombe Mawe, G., Moeyersons, J., Monsieurs, E., **Smets, B.**, Kervyn, M., **Dewitte, O.**, 2019. Questioning causes and drivers of slope instability in a tropical context – insights from the Ikoma Landslide (DR Congo). Geophysical Research Abstracts 21, EGU2019-7680, EGU General Assembly, Vienna, Austria, 07 - 12 April 2019 (Oral).

[22.] **Kervyn, F.**, **Laghmouch, M.**, **Michellier, C.**, **Smets, B.**, Huyse, T., **Dewitte, O.**, 2019. Natural hazards, risks and society in Africa: developing knowledge and capacities - the HARISSA project. Geophysical Research Abstracts 21, EGU2019-17520, EGU General Assembly, Vienna, Austria, 07 - 12 April 2019 (Oral).

[23.] Maki Mateseo, J.-C., Bielders, C., Monsieurs, E., **Depicker, A.**, **Smets, B.**, Tambala, T., Bagalwa Mateso, L., **Dewitte, O.**, 2019. Land cover change and landslide occurrecne: the rift flanks west of Lake Kivu (DR Congo). 100th Journée Luxembourgeoises de Géodynamique, Luxembourg, Luxembourg, 25-27 March 2019 (Poster).

[24.] **Mboga, N.**, Georganos, S., **Grippa, T.**, Lennert, M.,Vanhuysse, S., Wolff, E, 2019. Weakly supervised fully convolutional networks using OBIA classification output. 2019 Joint Urban Remote Sensing Event (JURSE), Vannes, France, 22-24 May 2019(Oral + Poster).

[25.] **Smets, B.**, **Michellier, C.**, Muganga, G., **Kervyn, F.**, **Dewitte, O.**, 2019. The city of Goma from 1947 to 2017: Time-Series of Orthophotos from Aerial Imagery. 100th Journée Luxembourgeoises de Géodynamique, Luxembourg, Luxembourg, 25-27 March 2019 (Poster).

2018

[26.] Dille, A., **Kervyn, F.**, Mugaruka Bibentyo, T., Delvaux, D., Ganza Bamulezi, G., Ilombe Mawe, G., Moeyersons, J., Monsieurs, E., **Smets, B.**, Kervyn, M**., Dewitte, O.**,2018. Questioning causes and drivers of slope instability in a tropical context – insights from the Ikoma Landslide (DR Congo). Young Researchers’ Overseas Day - Royal Academy for Overseas Sciences, Brussels, 07 December 2018 (Poster).

[27.] **Depicker, A.**, **Jacobs, L.**, Maki Mateso, J.-C., Delvaux, D., Havenith, H.-B., **Govers, G.**, **Dewitte, O.**, 2018. Aadded value of regional versus global landslide susceptibility: western branch of the East African Rift. Young Researchers’ Overseas Day - Royal Academy for Overseas Sciences, Brussels, 07 December 2018 (Poster).

[28.] Dille, A., **Kervyn, F.**, Malet, J.-P., d'Oreye, N., Kervyn, M., **Dewitte, O.**, 2018. Developing a multi-sensor approach to characterize Dynamics of slow-moving landslides in the tropical environments of Bukavu (DRC): from ground deformation analysis to hazard prediction. RMCA PhD Day, Tervuren, Belgium, 20 November 2018 (Oral).

[29.] **Dewitte, O.**, Mugaruka Bibentyo, T., Kulimushi Matabaro, S., Balegamire, C., Basimike, J., Delvaux, D., Dille, A., Ganza Bamulezi, G., **Michellier, C.**, Monsieurs, E., Birhenjira, E.M., Nshokano, J.-R., Nzolang, C., **Kervyn, F.**, 2018. Landslide hazard in Bukavu (DR Congo): a geomorphological assessment in a data-poor context. Grande conférence sur la géologie du Congo, Kinshasa, DR Congo, 24 – 25 October 2018 (Poster).

[30.] **Smets, B.**, Steyaert, L., **Michellier, C.**, Syavulisembo, A.M., Muganga, G., Barrière, J., d'Oreye, N., **Kervyn, F.**, 2018. Significant improvements provided by SfM-MVS photogrammetry for the study of active volcanism and related hazards and risks in the Virunga Volcanic Province. 6th International Geologica Belgica Meeting 2018 "Geology Serving Society", Leuven, Belgium, 12 – 14 September 2018 (Oral).

[31.] Mugaruka Bibentyo, T., Dille, A., Vanmaercke, M., **Dewitte, O.**, 2018. Landslide distribution in a changing environment: focus on the Ruzizi gorges located between DR Congo and Rwanda. 6th International Geologica Belgica Meeting 2018 "Geology Serving Society", Leuven, Belgium, 12 – 14 September 2018 (Poster).

[32.] Dille, A., **Kervyn, F.**, Ganza Bamulezi, G., Ilombe Mawe, G., Kalikone Buzera, C., Mugaruka Bibentyo, T., Safari Makito, E., Monsieurs, E., Delvaux, D., **Smets, B.**, **Dewitte, O.**, 2018. Characterising drivers and mechanisms of landsliding in a tropical context – Ikoma landslide, DR Congo. 6th International Geologica Belgica Meeting 2018 "Geology Serving Society", Leuven, Belgium, 12 – 14 September 2018 (Oral).

[33.] **Smets, B.**, **Michellier, C.**, Syavulisembo, A.M., Muganga, G., d'Oreye, N., **Kervyn, F.**, 2018. Very high-resolution imaging of the city of Goma (North Kivu, D.R. Congo) using SfM-MVS photogrammetry. IGARSS 2018, July 22-27, 2018, Valencia, Spain (Poster).

[34.] **Mboga, N.**, Georganos, S., **Grippa, T.**, **Lennert, M.**, **Vanhuysse, S.**, **Wolff, E.**, 2018. Fully convolutional networks for the classification of aerial VHR imagery. GEOBIA 2018 (Geobia in a changing world) conference, Montpelllier, France, 18-22 (Oral).

[35.] **Dewitte, O.**, Dille, A., Delvaux, D., **Michellier, C.**, Monsieurs, E., Nobile,A., Mugaruka Bibentyo, T., Basimike, **Jacobs, L.**, **Kervyn, F.**, 2017. Landslide hazard assessment in an urgan-sprawling context: a geomorphological approach in Bukavu (DR Congo). 19th Joint Geomorphological Meeting (JGM) "From field mapping and landform analysis to multi-risk assessment: Challenges, uncertainties and transdisciplinarity", Buzau, Romania, 16 – 20 May 2018 (Oral).

[36.] **Smets, B.**, Syavulisembo, A.M., **Michellier, C.**, d'Oreye, N., **Kervyn, F.**, 2018. Drone-based acquisition and SfM-MVS Photogrammetry as revolutions to study volcanoes and map the related hazards in complex tropical environment. Geophysical Research Abstracts 20, EGU2018-3630, EGU General Assembly, Vienna, Austria, 08 - 13 April 2018 (Oral).

[37.] Maki Mateseo, J.-C., Monsieurs, E., Bielders, C., **Dewitte, O.**, 2018. Landslides, land use and the anthropization of a rural environment: focus on the Rift flanks west of Lake Kivu (DR Congo). Geophysical Research Abstracts 20, EGU2018-5306, EGU General Assembly, Vienna, Austria, 08 - 13 April 2018 (Poster).

[38.] **Depicker, A.**, **Govers, G.**, **Van Rompaey, A.**, Havenith, H.-B., Maki Mateso, J.-C., **Dewitte, O.**, 2018. Landslides in a Changing Tropical Environment: North Tanganyika - Kivu Rift Zones. Geophysical Research Abstracts 20, EGU2018-6583, EGU General Assembly, Vienna, Austria, 08 - 13 April 2018 (Poster).

[39.] **Dewitte, O.**, **Depicker, A.**, **Mboga, N.**, **Laghmouch, M.**, **Michellier, C.**, **Smets, B.**, **Jacobs, L.**, **Kervyn, F.**, **Govers, G.**, **Van Rompaey, A.**, **Wolff, E.**, 2018. Landslides in a Changing Tropical Environment: North Tanganyika - Kivu Rift Zones. Geophysical Research Abstracts 20, EGU2018-6857, EGU General Assembly, Vienna, Austria, 08 - 13 April 2018 (Oral).

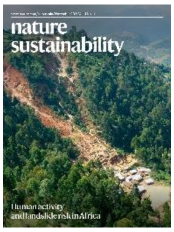
[40.] Dille, A., **Kervyn, F.**, Ganza Bamulezi, G., Ilombe Mawe, G., Kalikone Buzera, C., Mugaruka Bibentyo, T., Delvaux, D., **Smets, B.**, **Dewitte, O.**, 2018. High resolution characterisation of a recent landslide in a tropical environment. Geophysical Research Abstracts 20, EGU2018-15606, EGU General Assembly, Vienna, Austria, 08 - 13 April 2018 (Poster).

[41.] **Dewitte, O.**, Gryseels, G., 2018. From the field to reference collections for research for sustainable development in Africa. ISRIC Seminar: The World Soil Reference Collection: a unique source for research and education. Wageningen University and Research, Netherlands, 29 March 2018 (Oral).

[42.] **Dewitte, O.**, 2018. Landslide characterization in the Western Branch of the East. Geologica Belgica Van den Broeck medal 2018 laureate conference. University of Ghent, Belgium, 28 March 2018 (Oral).

Annex 3

International recognition



2021	Nature Sustainability cover (Vol. 4, 11, Nov. 2021) entitled “Human activity and landslide risk in Africa”. associated with the paper “Historical dynamics of landslide risk from population and forest-cover changes in the Kivu Rift” published by Depicker et al. (2021) in Nature Sustainability
2021	News & Views of Nature Sustainability “A more dynamic understanding of landslide risk” that explains our research paper entitled “Historical dynamics of landslide risk from population and forest-cover changes in the Kivu Rift” published by Depicker et al. (2021) in Nature Sustainability.
2021	European Geosciences Union highlights of our research paper entitled “Interactions between deforestation, landscape rejuvenation, and shallow landslides in the North Tanganyika - Kivu Rift region, Africa” published by Depicker et al. (2021) in Earth Surface Dynamics.

Annex 4

Media coverage from the Nature Sustainability manuscript

21/08/2021	MediaCongo: Les potentiels glissements de terrain dans le rift du Kivu sont liés à la déforestation https://www.mediacongo.net/article-actualite-92041_les_potentiels_glissements_de_terrain_dans_le_rift_du_kivu_sont_lies_a_la_deforestation.html
20/08/2021	Dworaczek: Les potentiels glissements de terrain dans le rift du Kivu sont liés à la déforestation https://dworaczek-bendome.org/v2/2021/08/les-potentiels-glissements-de-terrain-dans-le-rift-du-kivu-sont-lies-a-la-deforestation/?PageSpeed=noscript
20/08/2021	BELSPO/BEO: Landslide disaster risk in the Kivu Rift is linked to deforestation and population growth https://eo.belspo.be/en/news/landslide-disaster-risk-kivu-rift-linked-deforestation-and-population-growthl
20/08/2021	Terra Daily: Landslide disaster risk in the Kivu Rift is linked to deforestation and population growth https://www.terradaily.com/reports/Landslide_disaster_risk_in_the_Kivu_Rift_is_linked_to_deforestation_and_population_growth_999.html
20/08/2021	La Libre Afrique: Afrique centrale/ environnement : les potentiels glissements de terrain dans le rift du Kivu sont liés à la déforestation https://afrique.lalibre.be/63094/les-potentiels-glissements-de-terrain-dans-le-rift-du-kivu-sont-lies-a-la-deforestation/
20/08/2021	Business AM: Ontbossing en bevolkingsgroei gelinkt aan dodelijke aardverschuivingen in Kivu Rift https://businessam.be/ontbossing-en-bevolkingsgroei-gelinkt-aan-dodelijke-aardverschuivingen-in-kivu-rift/
20/08/2021	Xalima: Risque de glissements de terrain mortels dans le rift du Kivu : la déforestation et la croissance démographique seraient mes causes https://www.xalimasn.com/risque-de-glissements-de-terrain-mortels-dans-le-rift-du-kivu-la-deforestation-et-la-croissance-demographique-seraient-mes-causes/
19/08/2021	Environmental News Network (ENN): Landslide Disaster Risk in the Kivu Rift Is Linked to Deforestation and Population Growth https://www.enn.com/articles/68502-landslide-disaster-risk-in-the-kivu-rift-is-linked-to-deforestation-and-population-growth
20/08/2021	Eurasiareview: Landslide Disaster Risk In Kivu Rift Linked To Deforestation And Population Growth https://www.eurasiareview.com/20082021-landslide-disaster-risk-in-kivu-rift-linked-to-deforestation-and-population-growth/
19/08/2021	Samachar Central: Landslide disaster risk in the Kivu Rift is linked to deforestation and population growth https://samacharcentral.com/landslide-disaster-risk-in-the-kivu-rift-is-linked-to-deforestation-and-population-growth/

19/08/2021 EurekAlert: https://www.eurekalert.org/multimedia/782614

19/08/2021 DailyAdvent: Landslide Disaster Risk In Kivu Rift Linked To Deforestation And Population Growth https://www.dailyadvent.com/news/d90820ee8823f454afcd89caed85a754-Landslide-Disaster-Risk-In-Kivu-Rift-Linked-To-Deforestation-And-Population-Growth

19/08/2021 Dingiralfulbe: https://dingiralfulbe.com/les-potentiels-glissements-de-terrain-dans-le-rift-du-kivu-sont-lies-a-la-deforestation/

19/08/2021 Head Topics: Afrique centrale/ environnement : les potentiels glissements de terrain dans le rift du Kivu sont liés à la déforestation https://headtopics.com/be/afrique-centrale-environnement-les-potentiels-glissements-de-terrain-dans-le-rift-du-kivu-sont-li-21421812

19/08/2021 Afrique55: https://afrique55.com/les-potentiels-glissements-de-terrain-dans-le-rift-du-kivu-sont-lies-a-la-deforestation/n

19/08/2021 Pys.org: Landslide disaster risk in the Kivu Rift is linked to deforestation and population growth https://phys.org/news/2021-08-landslide-disaster-kivu-rift-linked.html

19/08/2021 Knack: Risico op aardverschuivingen in Kivu Rift is gelinkt aanontbossing en bevolkingsgroei https://trendstop.knack.be/nl/ontop/ondernemen/risico-op-aardverschuivingen-in-kivu-rift-is-gelinkt-aan-ontbossing-en-bevolkingsgroei-1068-1453389.aspx

19/08/2021 Proximus: Risico op aardverschuivingen in Kivu Rift is gelinkt aanontbossing en bevolkingsgroei https://www.proximus.be/pickx/nl/2164140/risico-op-aardverschuivingen-in-kivu-rift-is-gelinkt-aan-ontbossing-en-bevolkingsgroei

19/08/2021 Science Daily: Landslide disaster risk in the Kivu Rift is linked to deforestation and population growth https://www.sciencedaily.com/releases/2021/08/210819113015.htm

19/08/2021 Landslide disaster risk in the Kivu Rift is linked to deforestation and population growth https://phys.org/news/2021-08-landslide-disaster-kivu-rift-linked.html#google_vignette

19/08/2021 BELGA: les potentiels glissements de terrain dans le rift du Kivu sont liés à la déforestation https://uniq.auxiapp.be/Uniq/pdf/729/611F440202_729.pdf

19/08/2021 Alvinet: Afrique centrale/ environnement : les potentiels glissements de terrain dans le rift du Kivu sont liés à la déforestation https://www.alvinet.com/similaires/afrique-centrale-environnement-les-potentiels-glissements-de-terrain-dans-le-rift-du-kivu-sont-lies-a-la-deforestation/59836059

19/08/2021 Knowledia: Afrique centrale/environnement : les potentiels glissements de terrain dans le rift du Kivu sont liés à la déforestation https://news.knowledia.com/BE/fr/articles/afrique-centrale-environnement-les-potentiels-glissements-de-terrain-5dc20a7f9e3c1f7f60a9a8ffa13014052d9e87021

19/08/2021 MSN: Risico op aardverschuivingen in Kivu Rift is gelinkt aan ontbossing en bevolkingsgroei https://www.msn.com/nl-be/nieuws/nationaal/risico-op-aardverschuivingen-in-kivu-rift-is-gelinkt-aan-ontbossing-en-bevolkingsgroei/ar-AANvmOe?li=BBqj2K6&srcref=rss

19/08/2021 NotiUlti: El riesgo de desastres por deslizamientos de tierra en el Rift de Kivu está relacionado con la deforestación y el crecimiento de la población https://www.notiulti.com/el-riesgo-de-desastres-por-deslizamientos-de-tierra-en-el-rift-de-kivu-esta-relacionado-con-la-deforestacion-y-el-crecimiento-de-la-poblacion

19/08/2021 Nouvelles Du Monde: Le risque de glissement de terrain dans le Rift du Kivu est lié à la déforestation et à la croissance démographique https://www.nouvelles-du-monde.com/le-risque-de-glissement-de-terrain-dans-le-rift-du-kivu-est-lie-a-la-deforestation-et-a-la-croissance-demographique-sciencedaily

19/08/2021 RTBF: Afrique centrale/environnement : les potentiels glissements de terrain dans le rift du Kivu sont liés à la déforestation https://www.rtbf.be/info/monde/detail_afrique-centrale-environnement-les-potentiels-glissements-de-terrain-dans-le-rift-du-kivu-sont-lies-a-la-deforestation?id=10826541

19/08/2021 ULB: Glissements de terrain dans le Rift du Kivu: la déforestation et la croissance démographique en cause https://actus.ulb.be/fr/actus/recherche/la-deforestation-et-de-la-croissance-demographique-se-refletent-dans-le-risque-de-glissements-de-terrain-dans-le-rift-du-kivu

19/08/2021 KU Leuven Nieuws: "Landslide disaster risk in the Kivu Rift is linked to deforestation and population growth". https://nieuws.kuleuven.be/en/content/2021/landslide-disaster-risk-kivu-rift-linked-to-deforestation-and-population-growth

19/08/2021 RMCA – Sciences News: "Landslide disaster risk in the Kivu Rift is linked to deforestation and population growth". https://www.africamuseum.be/en/news/pasteca

REFERENCES

Note: papers (co-)authored by project partners are highlighted in bold

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services — A global review. Geoderma 262, 101–111. doi:10.1016/j.geoderma.2015.08.009

AghaKouchak, A., Chiang, F., Huning, L.S., Love, C.A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S.M., Ragno, E., Sadegh, M., 2020. Climate Extremes and Compound Hazards in a Warming World. Annual Review of Earth and Planetary Sciences 48, 1–30. doi:10.1146/annurev-earth-071719-055228

Agliardi, F., Scuderi, M.M., Fusi, N., Collettini, C., 2020. Slow-to-fast transition of giant creeping rockslides modulated by undrained loading in basal shear zones. Nature Communications 11, 1–11. doi:10.1038/s41467-020-15093-3

Albino, F., Smets, B., D'Oreye, N., Kervyn, F., 2015. High-resolution TanDEM-X DEM: An accurate method to estimate lava flow volumes at Nyamulagira volcano (D.R. Congo). Journal of Geophysical Research: Solid Earth 120, 4189–4207. doi:10.1002/2015JB011988

Anderson, M.G., Holcombe, E., 2013. Community-based landslide risk reduction: managing disasters in small steps. World Bank Publications.

Bakker, V., Verburg, P.H., van Vliet, J., 2021. Trade-offs between prosperity and urban land per capita in major world cities. Geography and Sustainability 2, 134–138. doi:10.1016/j.geosus.2021.05.004

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Mersey, B., Ferrer, E.A., 2011. Has the Earth's sixth mass extinction already arrived? Nature 471, 51–57. doi:10.1038/nature09678

Basnet, B., Vodacek, A., 2015. Tracking land use/land cover dynamics in cloud prone areas using moderate resolution satellite data: A case study in Central Africa. Remote Sensing 7, 6683–6709. doi:10.3390/rs70606683

Baumgartner, S., Bauters, M., Barthel, M., Alebadwa, S., Bahizire, N., Sumaili, C., Ngoy, D., Kongolo, M., Bazirake, B.M., Ntaboba, L.C., Six, J., Boeckx, P., Van Oost, K., Drake, T.W., 2022. Fluvial sediment export from pristine forested headwater catchments in the Congo Basin. Geomorphology 398, 108046. doi:10.1016/j.geomorph.2021.108046

Bédécarrats, F., Lafuente-Sampietro, O., Leménager, M., Lukono Sowa, D., 2019. Building commons to cope with chaotic urbanization? Performance and sustainability of decentralized water services in the outskirts of Kinshasa. Journal of Hydrology 573, 1096–1108. doi:10.1016/j.jhydrol.2016.07.023

Belay, K.T., Van Rompaey, A., Poesen, J., Van Bruyssel, S., Deckers, J., Amare, K., 2015. Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? Land Degradation and Development 26, 680–689. doi:10.1002/ldr.2275

Belward, A.S., Skøien, J.O., 2015. Who launched what, when and why; trends in global land-cover observation capacity from civilian earth observation satellites. ISPRS Journal of Photogrammetry and Remote Sensing 103, 115–128. doi:10.1016/j.isprsjprs.2014.03.009

Binder, C., Hinkel, J., Bots, P., Claudia, P.-W., 2013. Comparison of Frameworks for Analyzing Social-ecological Systems. Ecology and Society 18, 26. doi:10.5751/ES-05551-180426

Bradshaw, C.J.A., Sodhi, N.S., Peh, K.S.H., Brook, B.W., 2007. Global evidence that deforestation amplifies flood risk and severity in the developing world. Global Change Biology 13, 2379–2395. doi:10.1111/j.1365-2486.2007.01446.x

Broeckx, J., Vanmaercke, M., Duchateau, R., Poesen, J., 2018. A data-based landslide susceptibility map of Africa. Earth-Science Reviews 185, 102–121. doi:10.1016/j.earscirev.2018.05.002

Butsic, V., Baumann, M., Shortland, A., Walker, S., Kuemmerle, T., 2015. Conservation and conflict in the Democratic Republic of Congo: The impacts of warfare, mining, and protected areas on deforestation. Biological Conservation 191, 266–273. doi:10.1016/j.biocon.2015.06.037

Carey, J.M., Massey, C.I., Lyndsell, B., Petley, D.N., 2019. Displacement mechanisms of slow-moving landslides in response to changes in porewater pressure and dynamic stress. Earth Surface Dynamics 7, 707–722. doi:10.5194/esurf-7-707-2019

CRED UNDRR, 2020. Human cost of disasters: An overview of the last 20 years 2000-2019. Brussels, Belgium.

CRED UNISDR, 2018. Economic losses, poverty & disasters: 1998-2017, Centre for Research on the Epidemiology of Disasters, CRED. Geneva, Switzerland.

DeFries, R.S., Rudel, T., Uriarte, M., Hansen, M., 2010. Deforestation driven by urban population growth and agricultural trade in the twenty-first century. Nature Geoscience 3, 178–181. doi:10.1038/ngeo756

Delvaux, D., Mulumba, J.-L.L., Sebagenzi, M.N.S., Bondo, S.F., Kervyn, F., Havenith, H.-B., 2017. Seismic hazard assessment of the Kivu rift segment based on a new seismotectonic zonation model (western branch, East African Rift system). Journal of African Earth Sciences 134, 831–855. doi:10.1016/j.jafrearsci.2016.10.004

Depicker, A., Govers, G., Jacobs, L., Campforts, B., Uwihirwe, J., Dewitte, O., 2021a. Interactions between deforestation, landscape rejuvenation, and shallow landslides in the North Tanganyika-Kivu rift region, Africa. Earth Surface Dynamics 9, 445–462. doi:10.5194/esurf-9-445-2021

Depicker, A., Govers, G., Jacobs, L., Vanmaercke, M., Uwihirwe, J., Campforts, B., Kubwimana, D., Maki Mateso, J.-C., Mugaruka Bibentyo, T., Nahimana, L., Smets, B., Dewitte, O., to be submitted. Landslide mobilization rates in a changing tropical environment: the North Tanganyika-Kivu Rift region, Africa. Science of the Total Environment.

Depicker, A., Jacobs, L., Delvaux, D., Havenith, H.-B., Maki Mateso, J.-C., Govers, G., Dewitte, O., 2020. The added value of a regional landslide susceptibility assessment: the western branch of the East African Rift. Geomorphology 353, 106886. doi:10.1016/j.geomorph.2019.106886

Depicker, A., Jacobs, L., Mboga, N., Smets, B., Van Rompaey, A., Lennert, M., Wolff, E., Kervyn, F., Michellier, C., Dewitte, O., Govers, G., 2021b. Historical dynamics of landslide risk from population and forest-cover changes in the Kivu Rift. Nature Sustainability 4, 965–974. doi:10.1038/s41893-021-00757-9

Dewitte, O., Depicker, A., Moeyersons, J., Dille, A., 2022. Mass Movements in Tropical Climates, in: Shroder, J.J.F. (Ed.), Treatise on Geomorphology, Vol. 5. Elsevier, Academic Press, pp. 338–349. doi:10.1016/b978-0-12-818234-5.00118-8

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 18, 161–177. doi:10.1007/s10346-020-01452-0

Dewitte, O., Van Den Eeckhaut, M., Poesen, J., Demoulin, A., 2009. Decadal-scale analysis of ground movements in old landslides in western Belgium. Zeitschrift für Geomorphologie 53, 23–45. doi:10.1127/0372-8854/2009/0053-0023

Dille, A., Dewitte, O., Handwerger, A.L., D'Oreye, N., Derauw, D., Ganza Bamulezi, G., Ilombe Mawe, G., Michellier, C., Moeyersons, J., Monsieurs, E., Mugaruka Bibentyo, T., Samsonov, S., Smets, B., Kervyn, M.,

Kervyn, F., 2022. Acceleration of a large deep-seated tropical landslide due to urbanization feedbacks. Nature Geoscience 15, 1048–1055. doi:10.1038/s41561-022-01073-3

Dille, A., Kervyn, F., Handwerger, A.L., d'Oreye, N., Derauw, D., Mugaruka Bibentyo, T., Samsonov, S., Malet, J.-P., Kervyn, M., Dewitte, O., 2021. When image correlation is needed: unravelling the complex dynamics of a slow-moving landslide in the tropics with dense radar and optical time series. Remote Sensing of Environment 258, 112402. doi:10.1016/j.rse.2021.112402

Dille, A., Kervyn, F., Mugaruka Bibentyo, T., Delvaux, D., Bamulezi Ganza, G., Ilombe Mawe, G., Kalikone Buzera, C., Safari Makito, E., Moeyersons, J., Monsieurs, E., Nzolang, C., Smets, B., Kervyn, M., Dewitte, O., 2019. Causes and triggers of deep-seated hillslope instability in the tropics – insights from a 60-year record of Ikoma landslide (DR Congo). Geomorphology 345, 106835. doi:10.1016/j.geomorph.2019.106835

Emberson, R., Kirschbaum, D., Stanley, T., 2020. New Global Characterization of Landslide Exposure. Natural Hazards and Earth System Sciences 30, 1–21. doi:10.5194/nhess-2019-434

ESA Climate Change Initiative–Land Cover Project 2017. 20 m Resolution (European Space Agency, 2016).

Fletcher, T.D., Andrieu, H., Hamel, P., 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. Advances in Water Resources 51, 261–279. doi:10.1016/j.advwatres.2012.09.001

Froude, M.. J., Petley, D.N., 2018. Global fatal landslide occurrence from 2004 to 2016. Natural Hazards and Earth System Sciences 18, 2161–2181. doi:10.5194/nhess-18-2161-2018

Gariano, S.L., Guzzetti, F., 2016. Landslides in a changing climate. Earth-Science Reviews 162, 227–252. doi:10.1016/j.earscirev.2016.08.011

Godschalk, D.R., 2003. Urban Hazard Mitigation: Creating Resilient Cities. Natural Hazards Review 4, 136–143. doi:10.1061/(asce)1527-6988(2003)4:3(136)

Guzzetti, F., Gariano, S.L., Peruccacci, S., Brunetti, M.T., Marchesini, I., Rossi, M., Melillo, M., 2020. Geographical landslide early warning systems. Earth-Science Reviews 200, 102973. doi:10.1016/j.semcancer.2019.07.023

Handwerger, A.L., Booth, A.M., Huang, M.-H., Fielding, E.J., Bürgmann, R., 2019. A shift from drought to extreme rainfall drives a stable landslide to catastrophic failure. Scientific Reports 9, 1–12. doi:10.1038/s41598-018-38300-0

Handwerger, A.L., Roering, J.J., Schmidt, D. a., 2013. Controls on the seasonal deformation of slow-moving landslides. Earth and Planetary Science Letters 377-378, 239–247. doi:10.1016/j.epsl.2013.06.047

Hansen, M.C., Potapov, P. V, Moore, R., Hancher, M., Turubanova, S. a, Tyukavina, A., Thau, D., Stehman, S. V, Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853. doi:10.1126/science.1244693

Hilley, G.E., Bürgmann, R., Ferretti, A., Novali, F., Rocca, F., 2004. Dynamics of slow-moving landslides from permanent scatterer analysis. Science 304, 185–190. doi:10.1126/science.1098821

Holcombe, L., Beesley, M.E.W., Vardanega, P.J., Sorbie, R., 2016. Urbanisation and landslides: Hazard drivers and better practices. Proceedings of the Institution of Civil Engineers: Civil Engineering 169, 137–144. doi:10.1680/jcien.15.00044

Hope, K.R., 2008. Urbanization and Urban Growth in Africa. African and Asian Studies 33, 345–358. doi:10.1163/156852198x00104

Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types, an update. Landslides 11, 167–194. doi:10.1007/s10346-013-0436-y

Hurtt, G.C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B.L., Calvin, K., Doelman, J.C., Fisk, J., Fujimori, S., Goldewijk, K.K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J.O., Kennedy, J., Krisztin, T., Lawrence, D., Lawrence, P., Ma, L., Mertz, O., Pongratz, J., Popp, A., Poulter, B., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., Tubiello, F.N., van Vuuren, D.P., Zhang, X., 2020. Harmonization of global land use change and management for the period 850-2100 (LUH2) for CMIP6. Geoscientific Model Development 13, 5425–5464. doi:10.5194/gmd-13-5425-2020

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. BRAIN-BE 2.0 - Call for proposals 2022-2023 56/60 Yelekçi, R. Yu,and B. Zhou (eds.)]. Cambridge University Press. In Press. doi:10.1017/9781009157896.

IPCC, 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

Iverson, R.M., 2000. Landslide triggering by rain infiltration. Water Resources Research 36, 1897–1910.

Iverson, R.M., Major, J.J., 1987. Rainfall, ground-water flow, and seasonal movement at Minor Creek landslide, northwestern California: physical interpretation of empirical relations. Geological Society of America Bulletin 99, 579–594. doi:10.1130/0016-7606(1987)99<579:RGFASM>2.0.CO;2

Jacobs, L., Dewitte, O., Poesen, J., Delvaux, D., Thiery, W., Kervyn, M., 2016a. The Rwenzori Mountains, a landslide-prone region? Landslides 13, 519–536. doi:10.1007/s10346-015-0582-5

Jacobs, L., Maes, J., Mertens, K., Sekajugo, J., Thiery, W., Van Lipzig, N., Poesen, J., Kervyn, M., Dewitte, O., 2016b. Reconstruction of a flash flood event through a multi-hazard approach: focus on the Rwenzori Mountains, Uganda. Natural Hazards 84, 851–876. doi:10.1007/s11069-016-2458-y

James, M.R., Robson, S., Smith, M.W., 2017. 3-D uncertainty-based topographic change detection with structure-from-motion photogrammetry: precision maps for ground control and directly georeferenced surveys. Earth Surface Processes and Landforms. doi:10.1002/esp.4125

Joshi, N., Baumann, M., Ehammer, A., Fensholt, R., Grogan, K., Hostert, P., Jepsen, M.R., Kuemmerle, T., Meyfroidt, P., Mitchard, E.T. a, Reiche, J., Ryan, C.M., Waske, B., 2016. A review of the application of optical and radar remote sensing data fusion to land use mapping and monitoring. Remote Sensing 8, 1–23. doi:10.3390/rs8010070

Kii, M., 2021. Projecting future populations of urban agglomerations around the world and through the 21st century. npj Urban Sustainability 1. doi:10.1038/s42949-020-00007-5

Lacroix, P., Handwerger, A.L., Bièvre, G., 2020. Life and death of slow-moving landslides. Nature Reviews Earth & Environment 1, 404–419. doi:10.1038/s43017-020-0072-8

Laghmouch, M., Kalikone, C., Ilombe, G., Ganza, G., Delvaux, D., Safari, E., Bachinyaga,J., Wazi, N., Nzolang, C., Fernandez-Alonso, M., Nimpagaritse, G., Tack, L.,Dewaele, S., Kervyn, F., 2018. Carte géologique du Kivu au 1/500 000. Tervuren, Belgium: RMCA; Bukavu, DRC: Université Officielle de Bukavu.

Laghmouch, M., Nimpagaritse, G., Mudende, L., Minani, M., Ndereyimana, J., Icitegetse, I., Naahimana, A., Ndarihonyoye, P., Niyongabo, J.B., Kervyn, F., 2018b. Numérisation de la Carte Géologique au 50,000 ème; Ministère de l'Hydraulique, de l'Energie et des Mines; République du Burundi & Musée royal de l'Afrique Ccentrale (MRAC), Tervuren, Belgium, 2018; ISBN 978949224429.

Lambin, E.F., Geist, H., 2006. Land-Use and Land-Cover Change: Local Processes and Global Impacts. Springer-Verlag, Berlin Heidelberg.

Larsen, M.C., 2008. Rainfall-triggered landslides , anthropogenic hazards , and mitigation strategies. Advances in Geosciences 14, 147–153.

Lerner, D.N., 2002. Identifying and quantifying urban recharge: A review. Hydrogeology Journal 10, 143–152. doi:10.1007/s10040-001-0177-1

Lewis, S.L., Edwards, D.P., Galbraith, D., 2015. Increasing human dominance of tropical forests. Science 349, 827–832. doi:10.1126/science.aaa9932.

Liu, J., Mooney, H., Hull, V., Davis, S., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K., Gleick, P., Kremen, C., Li, S., 2015. Systems integration for global sustainability. Science 347, 963. doi:10.1016/j.cognition.2008.05.007

Lopez-Saez, J., Corona, C., Eckert, N., Stoffel, M., Bourrier, F., Berger, F., 2016. Impacts of land-use and land-cover changes on rockfall propagation: Insights from the Grenoble conurbation. Science of the Total Environment 547, 345–355. doi:10.1016/j.scitotenv.2015.12.148

Luyssaert, S., Jammet, M., Stoy, P.C., Estel, S., Pongratz, J., Ceschia, E., Churkina, G., Don, A., Erb, K., Ferlicoq, M., Gielen, B., Gr"unwald, T., Houghton, R. a, Klumpp, K., Knohl, A., Kolb, T., Kuemmerle, T., Laurila, T., Lohila, A., Loustau, D., McGrath, M.J., Meyfroidt, P., Moors, E.J., Naudts, K., Novick, K., Otto, J., Pilegaard, K., Pio, C. a, Rambal, S., Rebmann, C., Ryder, J., Suyker, A.E., Varlagin, A., Wattenbach, M., Dolman, a J., 2014. Land management and land-cover change have impacts of similar magnitude on surface temperature. Nature Climate Change 4, 1–5. doi:10.1038/nclimate2196

Maes, J., Kervyn, M., de Hontheim, A., Dewitte, O., Jacobs, L., Mertens, K., Vanmaercke, M., Vranken, L., Poesen, J., 2017. Landslide risk reduction measures: A review of practices and challenges for the tropics. Progress in Physical Geography 41, 191–221. doi:10.1177/0309133316689344

Makanzu Imwangana, F., Dewitte, O., Ntombi, M., Moeyersons, J., 2014. Topographic and road control of mega-gullies in Kinshasa (DR Congo). Geomorphology 217, 131–139. doi:10.1016/j.geomorph.2014.04.021

Marc, O., Hovius, N., 2015. Amalgamation in landslide maps: effects and automatic detection. Natural Hazards and Earth System Sciences 15, 723–733. doi:10.5194/nhess-15-723-2015

Mboga, N., Aronco, S.D., Grippa, T., Pelletier, C., Georganos, S., Vanhuysse, S., Smets, B., Dewitte, O., Lennert, M., Wegner, J.D., 2021. Domain Adaptation for Semantic Segmentation of Historical Panchromatic Orthomosaics in Central Africa. ISPRS International Journal of Geo-Information 10, 523. doi:https://doi.org/10.3390/ijgi10080523

Mboga, N., Georganos, S., Grippa, T., Lennert, M., Vanhuysse, S., Wolff, E., 2019. Fully convolutional networks for the classification of aerial VHR imagery. Remote Sensing 11, 597. doi:10.3390/rs11050597

Mboga, N., Grippa, T., Georganos, S., Vanhuysse, S., Smets, B., Dewitte, O., Wolff, E., Lennert, M., 2020. Fully convolutional networks for land cover classification from historical panchromatic aerial photographs. ISPRS Journal of Photogrammetry and Remote Sensing 167, 385–395. doi:10.1016/j.isprsjprs.2020.07.005

Mboga, N., Michellier, C., Depicker, A., Grippa, T., Georganos, S., Vanhuysse, S., Smets, B., Kubwimana, D., Kervyn, F., Dewitte, O., Wolff, E., van Vliet, J., in review. Natural hazards and conflict dynamics as drivers of the long-term development of three cities in the East African Rift Valley. Land Use Policy.

Meditz, S. W., Merrill, T., 1994. Zaire: A Country Study 4th edn, Library of Congress Federal Research Division.

Merz, B., Blöschl, G., Vorogushyn, S., Dottori, F., Aerts, J.C.J.H., Bates, P., Bertola, M., Kemter, M., Kreibich, H., Lall, U., Macdonald, E., 2021. Causes, impacts and patterns of disastrous river floods. Nature Reviews Earth & Environment. doi:10.1038/s43017-021-00195-3

Meyfroidt, P., Carlson, K.M., Fagan, M.E., Gutiérrez-Vélez, V.H., Macedo, M.N., Curran, L.M., DeFries, R.S., Dyer, G. a, Gibbs, H.K., Lambin, E.F., Morton, D.C., Robiglio, V., 2014. Multiple pathways of commodity crop expansion in tropical forest landscapes. Environmental Research Letters 9, 074012. doi:10.1088/1748-9326/9/7/074012

Meyfroidt, P., Lambin, E.F., 2011. Global forest transition: Prospects for an end to deforestation, Annual Review of Environment and Resources. doi:10.1146/annurev-environ-090710-143732

Michellier, C., Delvaux, D., D'Oreye, N., Dewitte, O., Havenith, H.-B., Kervyn, M., Poppe, S., Trefon, T., Wolff, E., Kervyn, F., 2018. Geo-risk in Central Africa: Integrating Multi-Hazards and Vulnerability to Support Risk Management. Final Report. Brussels: Belgian Science Policy - 176 p.

Michellier, C., Pigeon, P., Kervyn, F., Wolff, E., 2016. Contextualizing vulnerability assessment: a support to geo-risk management in Central Africa. Natural Hazards 82, 27–42. doi:10.1007/s11069-016-2295-z

Molina, A., Vanacker, V., Balthazar, V., Mora, D., Govers, G., 2012. Complex land cover change, water and sediment yield in a degraded andean environment. Journal of Hydrology 472-473, 25–35. doi:10.1016/j.jhydrol.2012.09.012

Monsieurs, E., Dewitte, O., Depicker, A., Demoulin, A., 2019. Towards a transferable antecedent rainfall–susceptibility threshold approach for landsliding. Water 11, 2202. doi:10.3390/w11112202

Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. Proceedings of the National Academy of Sciences of the United States of America 104, 13268–13272. doi:10.1073/pnas.0611508104

Nkwunonwo, U.C., Whitworth, M., Baily, B., 2020. A review of the current status of flood modelling for urban flood risk management in the developing countries. Scientific African 7, e00269. doi:10.1016/j.sciaf.2020.e00269

Ordway, E.M., 2015. Political shifts and changing forests: Effects of armed conflict on forest conservation in Rwanda. Global Ecology and Conservation 3, 448–460. doi:10.1016/j.gecco.2015.01.013

Ostberg, S., Schaphoff, S., Lucht, W., Gerten, D., 2015. Three centuries of dual pressure from land use and climate change on the biosphere. Environmental Research Letters 10, 044011. doi:10.1088/1748-9326/10/4/044011

Ozturk, U., Bozzolan, E., Holcombe, E.A., Shukla, R., Pianosi, F., Wagener, T., 2022. How climate change and unplanned urban sprawl bring more landslides. Nature 608, 262–262.

Pelletier, J.D., Murray, A.B., Pierce, J.L., Bierman, P.R., Breshears, D.D., Crosby, B.T., Ellis, M., Foufoula-Georgiou, E., Heimsath, A.M., Houser, C., Lancaster, N., Marani, M., Merritts, D.J., Moore, L.J., Pederson, J.L., Poulos, M.J., Rittenour, T.M., Rowland, J.C., Ruggiero, P., Ward, D.J., Wickert, A.D., Yager, E.M., 2015. Earth ' s Future Forecasting the response of Earth ' s surface to future climatic and land use changes : A review of methods and research needs Earth ' s Future. Earth Future 3, 220–251. doi:10.1002/2014EF000290.Received

Price, K., 2011. Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. Progress in Physical Geography 35, 465–492. doi:10.1177/0309133311402714

Raju, E., Boyd, E., Otto, F., 2022. Stop blaming the climate for disasters. Communications Earth & Environment 3, 21–22. doi:10.1038/s43247-021-00332-2

Rengers, F.K., McGuire, L.A., Kean, J.W., Staley, D.M., Hobley, D.E.J., 2016. Model simulations of flood and debris flow timing in steep catchments after wildfire. Water Resources Research 52, 6041–6061. doi:10.1002/2015WR018176

Sapountzaki, K., Michellier, C., Pigeon, P., Rebotier, J., Daskalakis, I., 2022. A Risk-Based Approach to Development Planning, Disaster Risk Reduction for Resilience. doi.org/10.1007/978-3-030-99063-3_12

Satterthwaite, D., Huq, S., Pelling, M., Hannah R., Lankao, P. R., 2007. Adapting to Climate Change in Urban Areas: The Possibilities and Constraints in Low- and Middle-Income Nations. IIED.

Schuster, R.L., Highland, L.M., 2007. The third hans cloos lecture. Urban landslides: Socioeconomic impacts and overview of mitigative strategies. Bulletin of Engineering Geology and the Environment 66, 1–27. doi:10.1007/s10064-006-0080-z

Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences of the United States of America 109, 16083–16088. doi:10.1073/pnas.1211658109

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., 2012. Changes in climate extremes and their impacts on the natural physical environment. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, in: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., M. Tignor, and P.M.M. (Eds.), A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109–230.

Shroder, J., Papale, P., 2014. Volcanic Hazards, Risks, and Disasters, Coastal and Marine Hazards, Risks, and Disasters. Elsevier. doi:10.1016/B978-0-12-394846-5.01001-8

Sidle, R.C., Bogaard, T.A., 2016. Dynamic earth system and ecological controls of rainfall-initiated landslides. Earth-Science Reviews 159, 275–291. doi:10.1016/j.earscirev.2016.05.013

Sidle, R.C., Ziegler, A.D., Negishi, J.N., Nik, A.R., Siew, R., Turkelboom, F., 2006. Erosion processes in steep terrain—Truths, myths, and uncertainties related to forest management in Southeast Asia. Forest Ecology and Management 224, 199–225. doi:10.1016/j.foreco.2005.12.019

Smets, B., Kervyn, M., d'Oreye, N., Kervyn, F., 2015. Spatio-temporal dynamics of eruptions in a youthful extensional setting: Insights from Nyamulagira Volcano (D.R. Congo), in the western branch of the East African Rift. Earth-Science Reviews 150, 305–328. doi:10.1016/j.earscirev.2015.08.008

Smets, B., Michellier, C., Syavulisembo, A.M., Munganga, G., D'Oreye, N., Kervyn, F., 2018. Very high-resolution imaging of the city of goma (North Kivu, DR Congo) using SFM-MVS photogrammetry. IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium 3370–3373. doi:10.1109/IGARSS.2018.8517412

Smets, B., Tedesco, D., Kervyn, F., Kies, A., Vaselli, O., Yalire, M.M., 2010. Dry gas vents ("mazuku") in Goma region (North-Kivu, Democratic Republic of Congo): Formation and risk assessment. Journal of African Earth Sciences 58, 787–798. doi:10.1016/j.jafrearsci.2010.04.008

Smittarello, D., Smets, B., Barrière, J., Michellier, C., Oth, a., Shreve, T., Grandin, R., Theys, N., Brenot, H., Cayol, V., Allard, P., Caudron, C., Chevrel, O., Darchambeau, F., de Buyl, P., Delhaye, L., Derauw, D., Ganci, G., Geirsson, H., Kamate Kaleghetso, E., Kambale Makundi, J., Kambale Nguomoja, I., Kasereka Mahinda, C., Kervyn, M., Kimanuka Ruriho, C., Le Mével, H., Molendijk, S., Namur, O., Poppe, S., Schmid, M., Subira, J., Wauthier, C., Yalire, M., d'Oreye, N., Kervyn, F., Syavulisembo Muhindo, a., 2022. Precursor-free eruption triggered by edifice rupture at Nyiragongo volcano. Nature 609, 83–88. doi:10.1038/s41586-022-05047-8

Stanley, T., Kirschbaum, D.B., 2017. A heuristic approach to global landslide susceptibility mapping. Natural Hazards 87, 145–164. doi:10.1007/s11069-017-2757-y

Tanyaş, H., Görüm, T., Kirschbaum, D., Lombardo, L., 2022. Could road constructions be more hazardous than an earthquake in terms of mass movement? Natural Hazards. doi:10.1007/s11069-021-05199-2

Tellman, B., Sullivan, J.A., Kuhn, C., Kettner, A.J., Doyle, C.S., Brakenridge, G.R., Erickson, T.A., Slayback, D.A., 2021. Satellite imaging reveals increased proportion of population exposed to floods. Nature 596, 80–86. doi:10.1038/s41586-021-03695-w

Turner, B.L., Lambin, E.F., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. Proceedings of the National Academy of Sciences of the United States of America 104, 20666–20671. doi:10.1073/pnas.0704119104

USGS, 2006. Shuttle Radar Topography Mission, Global Land Cover Facility 1 Arc-Second, University of Maryland, College Park, Maryland.

Van de Walle, J., Thiery, W., Brousse, O., Souverijns, N., Demuzere, M., van Lipzig, N.P.M., 2020. A convection-permitting model for the Lake Victoria Basin: evaluation and insight into the mesoscale versus synoptic atmospheric dynamics. Climate Dynamics 54, 1779–1799. doi:10.1007/s00382-019-05088-2

Van Rompaey, A.J.J., Govers, G., Puttemans, C., 2002. Modelling land use changes and their impacts on soil erosion and sediment supply to rivers. Earth Surface Processes and Landforms 27, 481–494. doi:10.1002/esp.335

Van Vliet, J., de Groot, H.L.F., Rietveld, P., Verburg, P.H., 2015. Manifestations and underlying drivers of agricultural land use change in Europe. Landscape and Urban Planning 133, 24–36. doi:10.1016/j.landurbplan.2014.09.001

Vanacker, V., Vanderschaeghe, M., Govers, G., Willems, E., Poesen, J., Deckers, J., De Bievre, B., 2003. Linking hydrological, infinite slope stability and land-use change models through GIS for assessing the impact of deforestation on slope stability in high Andean watersheds. Geomorphology 52, 299–315.

Vanmaercke, M., Poesen, J., Van Mele, B., Demuzere, M., Bruynseels, A., Golosov, V., Bezerra, J.F.R., Bolysov, S., Dvinskih, A., Frankl, A., Fuseina, Y., Guerra, A.J.T., Haregeweyn, N., Ionita, I., Makanzu Imwangana, F., Moeyersons, J., Moshe, I., Nazari Samani, A., Niacsu, L., Nyssen, J., Otsuki, Y., Radoane, M., Rysin, I., Ryzhov, Y. V., Yermolaev, O., 2016. How fast do gully headcuts retreat? Earth-Science Reviews 154, 336–355. doi:10.1016/j.earscirev.2016.01.009

Verburg, P.H., Erb, K.H., Mertz, O., Espindola, G., 2013. Land System Science: Between global challenges and local realities. Current Opinion in Environmental Sustainability 5, 433–437. doi:10.1016/j.cosust.2013.08.001

Vervisch, T., Titeca, K., Vlassenroot, K., Braeckman, J., 2013. Social Capital and Post-Conflict Reconstruction in Burundi: The Limits of Community-based Reconstruction. Development and Change 44, 147–174. doi:10.1111/dech.12008

Willemen, L., Barger, N.N., Brink, B. Ten, Cantele, M., Erasmus, B.F.N., Fisher, J.L., Gardner, T., Holland, T.G., Kohler, F., Kotiaho, J.S., von Maltitz, G.P., Nangendo, G., Pandit, R., Parrotta, J. a., Potts, M.D., Prince, S.D., Sankaran, M., Brainich, A., Montanarella, L., Scholes, R., 2020. How to halt the global decline of lands. Nature Sustainability 3, 164–166. doi:10.1038/s41893-020-0477-x

Zscheischler, J., Seneviratne, S.I., 2017. Dependence of drivers affects risks associated with compound events. Science Advances 3, 1–11. doi:10.1126/sciadv.1700263