Effects of agricultural terraces on landslide occurrence: insights from a tropical mountainous region (Rwanda, Africa)

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ABSTRACT

Agricultural terraces are a commonly applied soil and water conservation strategy on steep and intensely cultivated hillslopes. Yet agricultural terraces can lead to an increased incidence of landslides. Nevertheless, their effects on hillslope stability remain poorly studied, especially in the tropical Global South, where terraces are increasingly implemented. Here we investigate to what extent the presence of such terraces may increase the incidence of landslides in the densely-populated northwestern Rwanda. For this, we mapped three important landslide events that were triggered by distinct and intense rainfall events in the region and analyzed the relation of these landslides to the presence of terraces and other controlling factors. Based on an inventory of >4,600 mostly shallow landslides in these three events, we show that landslides are about three times more likely to occur on terraced hillslopes as compared to non-terraced hillslopes. However, our results also demonstrate important variability between the events. While the effect was most pronounced for the largest 2020-event, the other two events, 2016 and 2018, showed a less clear or even negative impact of terracing on landslide occurrence. Furthermore, we observed this effect mainly on moderately to highly susceptible hillslopes and less so in areas with a very high landslide susceptibility. Landslides on terraces also tend to be slightly smaller than their counterparts in non-terraced areas. These findings have important implications for both landslide susceptibility assessment and land management.

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1. Introduction

Landslides are common and often impactful hillslope hazards caused by a range of natural and/or human-induced controlling factors (Sidle and Bogaard, 2016). For example, hillslopes of similar morphologies but underlain by different lithologies can lead to landslides of different types, sizes and frequencies (Clarke and Burbank, 2010; Mugaruka Bibentyo et al., 2024). Landsliding is also often influenced by vegetation characteristics (Gabet and Dunne, 2002; Zhou et al., 2002; Glade, 2003; Rickli and Graf, 2009; Wolter et al., 2010; Maki Mateso et al., 2023) as well as by land management practices that modify hillslope morphology (Schuster and Highland, 2001; Glade, 2003; Crosier and Glade, 2005; Petley et al., 2007; Glade et al., 2012; Chen and Huang, 2013). One of the most widely applied and significant anthropogenic hillslope modifications is agricultural terraces (Brown et al., 2021). Agricultural terraces are often implemented as a soil and water conservation measure (Gardner and Gerrard, 2003; Londoño 2008; Dotterweich, 2013; Deng et al., 2021; Rutebuka et al., 2021) or to increase land productivity (Posthumus, 2005; Rutebuka et al., 2021). More specifically, agricultural terracing reshapes natural slopes in a series of steep walls (or risers) and flat surfaces (treads), often consisting of unconsolidated material (Brown et al., 2021; Dorren and Rey, 2004; FAO, 2000). This not only leads to local increases in soil/regolith but also reduces hillslope runoff and increases water infiltration, resulting in overall higher moisture contents (Crosta et al., 2003; Sidle et al., 2006; Arnáez et al., 2015; Al Qudah et al., 2016).

Yet, these effects may also come with downsides. Studies indicate that agricultural terraces can lead to slope failure mechanisms of different types (Crosta et al., 2003; Turkelboom et al., 2008; Cevasco et al., 2013; Agnoletti et al., 2019), resulting in potentially increased landslide susceptibility, frequencies and/or sizes (Crosta et al., 2003; Chen et al., 2023). Nevertheless, the effects of agricultural terraces on landsliding remain poorly studied, especially in the tropical Global South (Sidle et al., 2006; Lewis et al., 2015; Wei et al., 2016). This corresponds to an overall lack of research on landslide occurrence, susceptibility, hazard and risks in these regions, especially in sub-Saharan Africa (Gariano and Guzzetti, 2016; Maes et al., 2017; Broeckx et al.,

2018; Reichenbach et al., 2018; Dewitte et al., 2022). Tropical mountainous regions of the Global South are among the most critical regions in terms of landslide risks. The naturally high landslide susceptibility of these regions, combined with their high population density, land use pressure, and associated land use changes such as deforestation and urbanization, often increase the exposure of an already vulnerable population to landslide hazards (Seto et al., 2012; Lewis et al., 2015; Depicker et al., 2021b; Dille et al., 2022; Ozturk et al., 2022). It is also in these tropical, densely-populated regions that agricultural terraces have often been implemented at massive scales (Williams, 1990; Posthumus, 2005; Amsalu and de Graaff, 2006; de Graaff et al., 2008). From an erosion-control and agricultural perspective, the construction of such terraces may be a valid choice (e.g., Brown et al., 2021; Deng et al., 2021; Uwacu et al., 2021). Nonetheless, as terracing may potentially also lead to more landsliding, its implementation involves important tradeoffs. Insight into such matters is therefore crucial for better catchment management strategies. Yet, there is very little quantitative data on whether the implementation of terraces indeed affects landslide incidence in the tropics and, if so, under which circumstances.

Hence, the goal of our work is to study the effects of agricultural terraces on landslide incidence in a densely-inhabited tropical landscape. To reach this goal we target the mountainous region of northwestern Rwanda (Africa), a landslide-prone area (Depicker et al., 2020; Dewitte et al., 2021) whose landscape has been reshaped by introducing agricultural terracing (Bizoza, 2011; Kagabo et al., 2013; Rutebuka et al., 2021). More specifically, focusing on recent rainfall-induced landslide events, we investigate the effects of terraces on landslide characteristics (frequency, size, and type) through exploring the role of slope, lithology, and regional landslide susceptibility patterns on their occurrence.

2. Material and Methods

2.1. Study area

Lying within the western branch of the landslide-prone East African Rift (Broeckx et al., 2018; Dewitte et al., 2021; Depicker et al., 2021a), the mountainous landscape of the study area is characterized by a tropical climate with a wet season from September to May and a dry season from June to August, and an average annual rainfall of about 1200 mm (Ministry of Environment, 2018). Overall, the susceptibility to landsliding of this landscape (Depicker et al., 2020) is

controlled by its steep hillslopes and sometimes deeply weathered lithology (Fig. 1C.) (Depicker et al., 2021a; Dewitte et al., 2021).

The region is often referred to as the "breadbasket" of the country and is intensely cultivated, with 90% of the population involved in agricultural activities (Ministry of Environment, 2018). Its high demographic pressure (~700 inhabitants/km²) and land scarcity result in intensive land use/cover changes through the conversion of forests into agricultural and built-up lands (Nambajimana et al., 2020). This leads to land overexploitation as well as problems of land degradation and soil erosion (Lewis, 1992; Lewis and Nyamulinda, 1996; Roose and Ndayizigiye, 1997; Turkelboom et al., 2008; Kuria et al., 2019). To cope with that problem, agricultural terracing has been promoted as a measure to stabilize soil erosion and enhance land productivity; the implementation of these terraces being particularly intense since 2010 (Bizoza 2011; Kagabo et al., 2013; Rutebuka et al., 2021).

The common types of terraces in the area are bench, locally called radical, and progressive (forming gradually) terraces (Fig.2). Radical terraces are a series of horizontal or almost horizontal strips running perpendicular to the slope direction at certain vertical intervals, supported by steep risers (Mesfin, 2016). During their construction, workers carefully remove the topsoil to a depth of around 30 cm (Fashaho et al., 2020) and work on the subsoil to create the bench surface (alternating the cut and fill work), after which the topsoil is spread back onto the surface. Generally, those terraces are of a size of between 2 m and 4 m in width, and the riser can reach 2.5 m (Fig. 2A, B and C). Stabilization is typically made by planting grass on the vertical face of the riser. Progressive terraces are built with the use of contour bunds, ridges, and ditches made of soil or stones that are placed across the slope direction along the contour. They gradually form over time as a result of erosion, farming activities, and deposition (Mesfin, 2016). Planting grass on the structure creates stability, just like in radical terraces (Van Dijk and Bruijnzeel, 2004; Rutebuka et al., 2021).

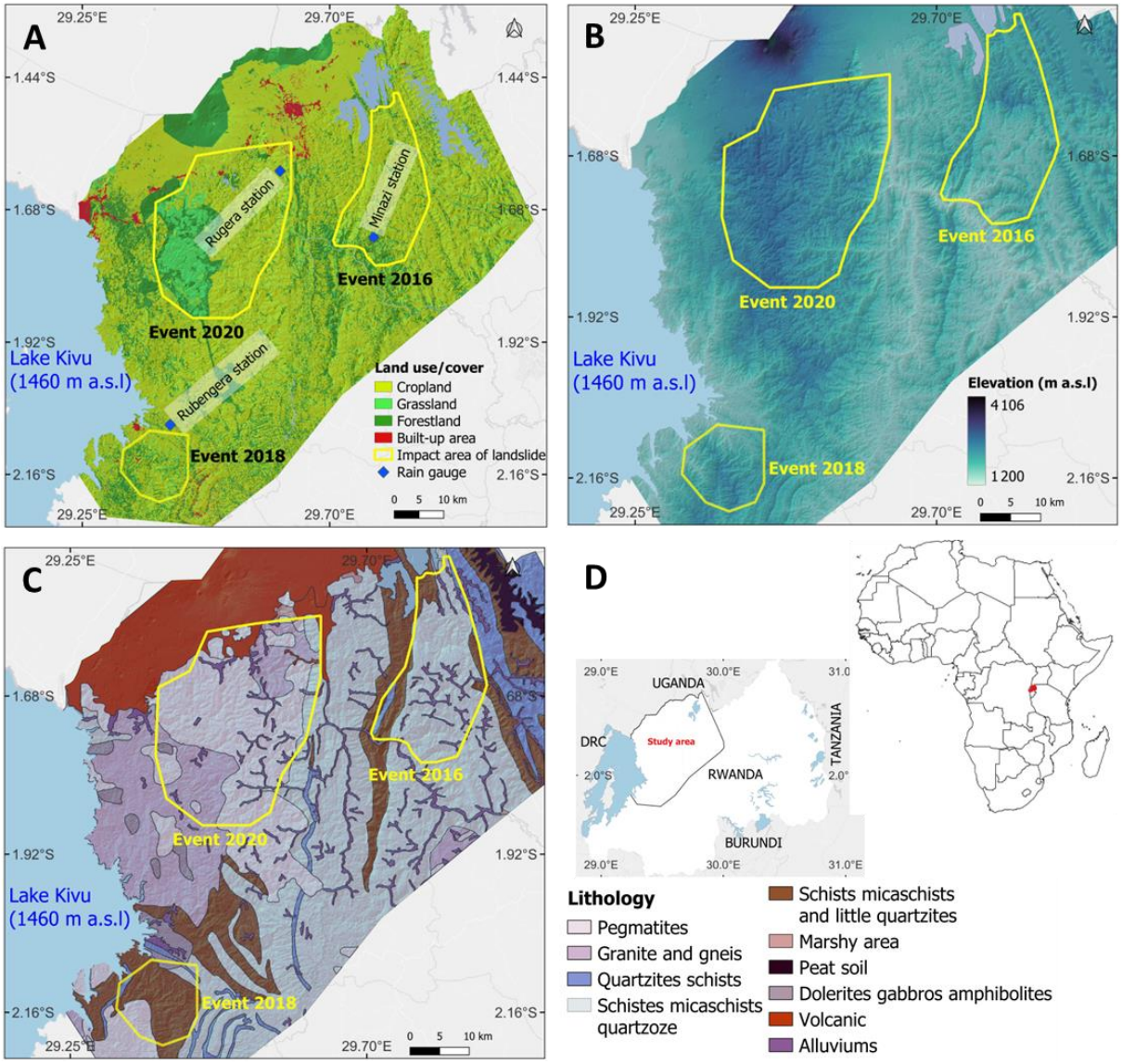

Fig. 1: Study area location and characteristics with the delineation of the three clustered zones impacted by the three rainfall-triggered landslide events analyzed in this research (see Section 2.2). **A)** Land use/cover in 2015 based on the Regional Centre for Mapping Resources and Development (RCMRD, 2015). **B)** Elevation based on the Japan Aerospace and Exploration DEM (JAXA, 2010). **C)** Lithology based on the geological map of Rwanda (Theunissen et al., 1991). **D)** Location of the study area.

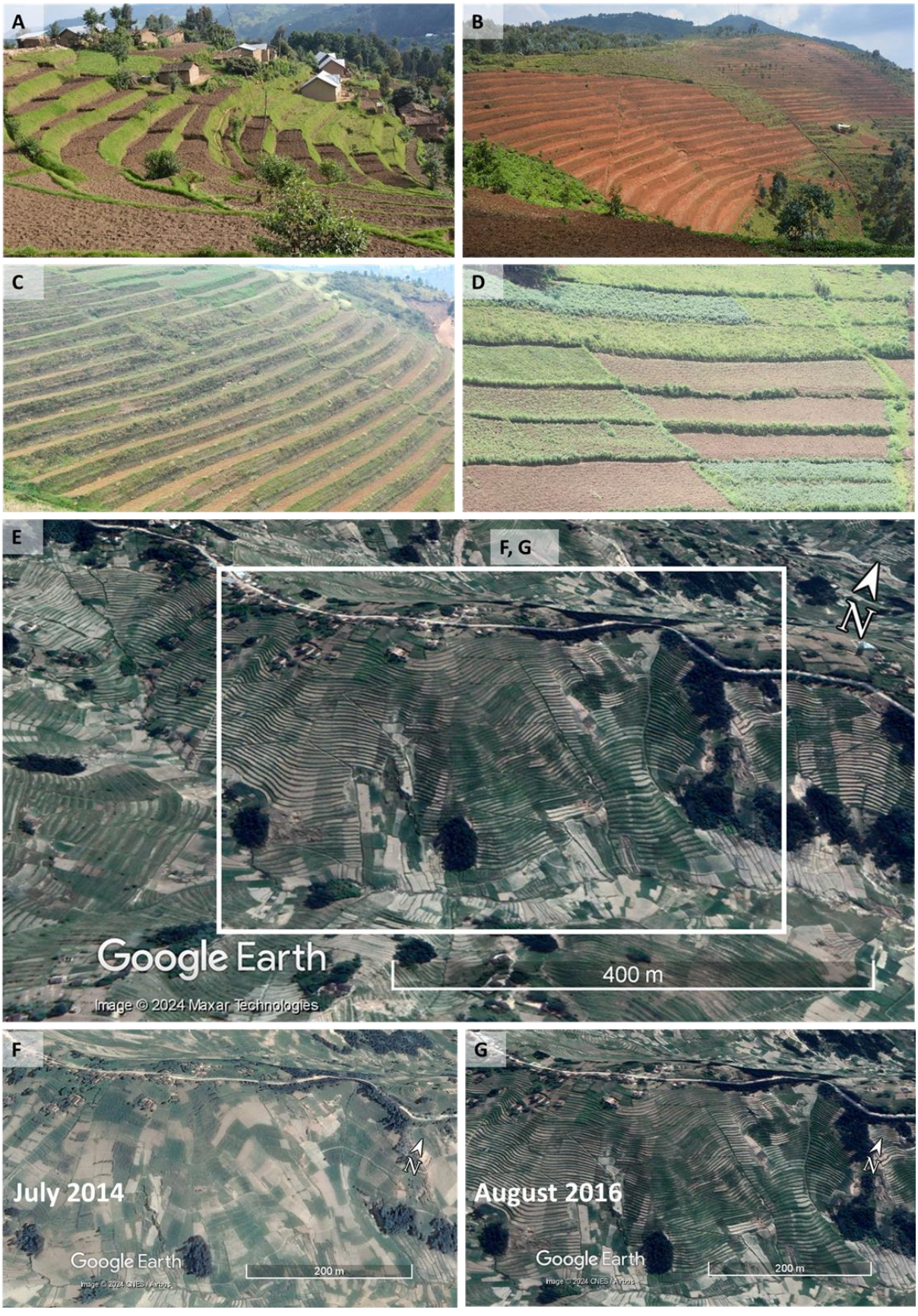
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Fig. 2: Example of agricultural terraces constructed in the study area. **A)** Radical terraces on pegmatite (picture taken in May 2021; 29°31'25.31"E, 1°40'01.48"S). **B)** and **C)** Radical terraces on quartzites-schists (pictures taken in September 2022; 29°23'24.72"E, 2°10'32.89"S and 29°22'57.30"E, 2°10'18.97"S, respectively). **D)** Progressive terrace on schist-micaschist (picture taken in October 2020; 29°51'15.46"E, 1°29'47.35"S). **E)**, **F)** and **G)** Evolution of a hillslope on pegmatite showing the construction of radical terraces between July 2014 and August 2016 (29°31'11.87"E, 1°42'40.85"S); imagery from Google Earth.

2.2 Landslide events

Our research investigates three rainfall-triggered landslide events that have occurred recently in the study area. These events are relatively important as compared to landslide events that are commonly observed in the East African Rift (Deijns et al., 2024; Niyokwiringirwa, et al., 2024). They are concentrated in three distinct spatial clustered zones (Fig. 1):

- The first event occurred on May 7 and 8, 2016 in the northern part of the region. According to the government of Rwanda, that event caused 24 deaths, damaged 118 houses and destroyed a large number of crops (MINEMA, 2018).
- The second event occurred on May 6, 2018 in the southwestern part of the study region (Dewitte et al., 2021; Deijns et al., 2022). This event caused 18 deaths, dozens of injuries, the destruction of 9,974 houses, and the loss of 4.5 km^2 of crops (Niyonzima, 2018).
- The third event occurred on May 1, 2020, in the northwestern part of the region and caused 28 deaths and the destruction of 450 houses as well as crops.

We compared rainfall characteristics associated with the occurrence of the three events based on daily rainfall information obtained from the rain gauges of the Rwanda Meteorological Agency (Meteo Rwanda, 2022) that were closest to each of them (Figure 3). Although uncertainties in rainfall assessment are associated with information at a daily level (Monsieurs et al., 2019) and the location of the rain gauge with respect to the location of the event (Monsieurs et al., 2018a), the use of this rain gauge information is more reliable for landslide event characterization than the use of precipitation products derived from earth observation (Monsieurs et al., 2018b; Nakulopa et al., 2022). We looked at the rainfall amounts on the day of the events and in the 2-day and 12-day periods that precede them. Such rainfall characteristics have been commonly used to study the triggering and antecedent rainfall conditions for landslides that occur outside the tropics (Guzzetti et al., 2007), but their application has also proven to be relevant in the region where our study area is located (Jacobs et al., 2016; Monsieurs et al., 2019; Uwihirwe et al., 2020). This rainfall

comparison shows that the events of 2018 and 2020 had overall similar rainfall amounts (Table 1). Yet, the event of 2016 was characterized by a much higher rainfall depth at the day of the event (Table 1). The three affected zones also show important contrasts in lithology (Table 2).

Table 1: Total rainfall amounts in the day(s) before each of the three landslide events, measured at the most nearby rain gauge station.

Landslide event	Rain gauge station	Rainfall (mm)		
		day of the event	2 days before the event	12 days before the event
2020	Rugera	83	18	159
2018	Rubengera	83	24	188
2016	Minazi	131	11	129

***Table 2*:** Lithology distribution within the clustered zones of the three landslide events (cf. **Fig. 1**). Lithology from Theunissen et al. (1991).

Lithology	Event 2016	Event 2018	Event 2020
Alluvial deposits	8 %	-	5%
Areas rich in green rocks (dolerite, gabbroas, amphibolites)	-	3%	1%
Granitic and gneissic rocks	-	-	24%
Pegmatite	-	16%	61%
Quartzites dominant on the schistose levels	4%	3%	-
Schists, quartz, michaschist and some quartzitic levels	72%	7%	-
Shales, micaschists and quartzites of little importance	16%	71%	5%
Volcanic rocks	-	-	4%

2.3. Constructing the landslide inventories

Visual interpretation of satellite images remains among the most widely used methods to build detailed landslide inventories that allow accurate characterization of the processes (Guzzetti et al., 2012; Casagli et al., 2023). A similar approach was followed to map the three rainfall-triggered landslide events discussed above. Some of the landslides triggered by these rainfalls had already

been mapped by Depicker et al. (2021a), Dewitte et al. (2021), and Deijns et al. (2022) through the visual interpretation of very high spatial resolution (< 1m) satellite images available in Google Earth. Here we completed these mapping efforts, making use of additional satellite imagery with similar resolution that was recently made available in Google Earth. The use of Google Earth imagery has been validated with high success to map landslides in the region of the study area (Sekajugo et al., 2022; Maki Mateso et al., 2023; Kanyiginya et al., 2024). On the other hand, the use of automatic classification for landslide inventory does not allow to reach the level of details needed to map the landslides for such an accurate analysis of the processes, especially in complex landscapes disturbed by human activities (Jones et al., 2021; Deiins et al., 2024). Here, in addition to the interpretation of the images, we conducted in-depth field observations and interviews with local residents over the period of February-March 2021 to validate more than 200 of the inventoried landslides, and confirm their time of occurrence.

Furthermore, we went beyond the simple delineation of the landslide boundaries, adding key landslide characteristics useful for our analyses. These include: determining the time range of available images (typically two to three months after the event's occurrence), and the type of landslides (based on the classification proposed by Hungr et al. (2014)). Furthermore, to better analyze those three landslide events, we manually positioned a point inside the source area of each landslide in order to accurately extract the corresponding environmental settings (e.g., Corominas et al., 2014; Bartelletti et al., 2017; Depicker et al., 2021a; Maki Mateso et al., 2023).

2.4. Controlling factors of landsliding

To link the occurrence and characteristics of the inventoried landslides to the potential presence of terraces, we delineated all terraced areas within each clustered zone of the events on the same satellite images that were used to map the landslides. In doing so, we recorded the type of terrace (i.e., progressive or radical). We assumed a landslide to occur in terraces if its identified source point was located within these mapped terraces.

We also extracted the hillslope angle of each landslide, which is one of the most important explanatory factors for landslide occurrence (Reichenbach et al., 2018). For this, we used the

ALOS PALSAR DEM at a resolution of 12.5 m (JAXA, 2010). This DEM is produced with radar images of 2006-2011, i.e., before the occurrence of the three studied events.

To have a further idea of the overall likelihood of landslide occurrence, we extracted the landslide susceptibility from a state-of-the-art regional landslide susceptibility map at 30-m resolution that covers our study region (Depicker et al., 2020). The data-driven model behind this map relied on a logistic regression approach and a set of twelve predictors: slope angle, north and east exposure, planar curvature, profile curvature, distance to the drainage network, land cover, lithostratigraphy, distance to active faults, distance to inactive faults, peak ground acceleration (PGA), and the 2-day 15 mm rainfall exceedance. The model was calibrated based on a comprehensive regional historical geomorphological inventory of more than 6,400 landslides of various ages (from recent years to tens of thousands of years), types and depth. The sensitivity of the model was tested against various landslide sampling strategies and successfully validated (with an AUC value for the ROC curve of 0.92; Depicker et al., 2020). As such, by considering a very broad variety of landslide processes associated with the geomorphological evolution of the region (Dewitte et al., 2021), this model represents the long-term landslide susceptibility of the landscape. The landslides of the model of Depicker et al. (2020) are not the landslides used in our study. Although the model uses land cover as a controlling factor, it is important to note that it did not consider the presence of agricultural terraces. As with slope steepness, we used the map to subdivide our study area based on the expected overall landslide susceptibility. For this, we used the original classes as proposed by Depicker et al. (2020). Furthermore, we used the continuous values of the logistic regression, ranging from 0 to 1, to evaluate its performance in predicting the locations of landslides for the three events. Additionally, we explored the potential added value of incorporating the presence of terraces as a predictor, as detailed in Section 2.5.3.

2.5. Statistical analyses

2.5.1. Frequency ratio

To analyze the potential link between landslide occurrence and the presence of agricultural terraces, we calculated the frequency ratios of landslides inside and outside terrace areas. Overall, the frequency ratio (FR) expresses how often landslides occur within a certain class of a potentially

controlling factor, controlled for how frequently that class occurs (e.g. Lee and Pradhan, 2007; Maki Mateso et al., 2023). It was calculated as follows:

$$FRi = \frac{{nL_i}/{nL_s}}{{A_i}/{A_S}} \quad \text{(Eq.1)}$$

where *FRi* is the frequency ratio for a certain class *i* of a considered controlling factor ; *nLi* is the number of landslides located in class *i* of the controlling factor; *nLs* is the total number of landslides in the study region (*S*); *Ai* is the area of *i*; and *As* is the area of the study region. A *FRi* > 1 indicates that landslides occur relatively more frequently in *i* than would be expected based on the spatial extent of this class.

We calculated the landslide density, in terraced and non-terraced areas for different classes of both slope angle and landslide susceptibility (cf. Section 2.4).

2.5.2. Odds ratio

As an additional measure to quantify the potential effect of terracing on landslide occurrence, we calculated the odds ratio for landslides occurring in terraced areas vs. landslides occurring in non-terraced areas. Again, this was done for different classes of slope angle and landslide susceptibility. The odds ratio (OR) was calculated as follows (Stoltzfus, 2011):

$$OR_i = \frac{{A_T}/{(1-A_T)}}{{A_{NT}}/{(1-A_{NT})}} = \frac{A_T \times (1-A_{NT})}{A_{NT} \times (1-A_T)} \quad \text{(Eq.2)}$$

where *ORi* is the odds ratio value for a certain class *i* of a considered controlling factor (e.g., of slope angle or landslide susceptibility); A_T is the total area of the landside affected area in terraces, located in class *i*; A_{NT} is the total landslide area in non-terraces, located in class *i*; 1-A_T is the spatial extent of the non-landslide affected area in terraces; and 1-A_{NT} is the spatial extent of the non-landslide affected area in non-terraced areas. Overall, the OR-value indicates how much more (OR >1) or less (OR <1) likely it is to find an area affected by landslides in terraced areas as compared to non-terraced areas.

2.5.3. Landslide susceptibility

It is outside the scope of this paper to predict the exact locations of landslides triggered by the three considered rainfall events. Nonetheless, our landslide inventories allow to evaluate how well a state-of-the-art regional landslide susceptibility model by Depicker et al. (2020) (described in section 2.4) could predict the spatial patterns of these new landslides. For this, we generated a

number of non-landslide points in each landslide event cluster. The location of these points was random, except for the fact that they were located at least 30 m away from a mapped landslide polygon. The number of zero points (non-landslide points) was set equal to the number of landslide points (e.g., Depicker et al., 2020). The share of the zero points was determined proportionally to the size of each affected area, which leads to a density of four points per km².

Using these zero-points as well as the mapped landslide source points, we constructed Receiver Operation Characteristic (ROC) curves for each event as well as the three events combined. ROC curves are a frequently used tool to assess the performance of landslide susceptibility models, with the corresponding Area Under the Curve (AUC) providing an overall metric of the discriminative ability of the model (Broeckx et al., 2018; Reichenbach et al., 2018). We constructed ROC curves for the original model of Depicker et al. (2020). In addition, we explored to what extent the performance of susceptibility models may be improved by incorporating the effect of terraces. For this, we fitted a simple logistic regression model based on two variables: the continuous landslide susceptibility value of the model by Depicker et al. (2020) and a dummy variable, indicating the presence (1) or absence (0) of terraces. Using a susceptibility model output as a predictor variable for another susceptibility assessment is in line with the approach of combining models done by, e.g., Depicker et al. (2020) and Rossi et al. (2010). The terrace variable was derived from our manually mapped terraces, where no further distinction was made between radical and progressive terraces (cf. Section 2.1). Most of the terraces in the three clustered zones have been implemented since 2014-2016. Logistic regressions were fitted in Python, using the *Logistic Regression* functionality of the *sklearn_linear_model* package (Pedregosa et al., 2011).

2.5.4. Landslide probability-size distributions

Earlier work demonstrated that sizes and corresponding frequencies of landslides triggered by a certain event such as intense rainfall typically follow a specific inverse-gamma distribution (Malamud et al., 2004). The comparison of such distributions from different landside events allows to understand the importance of natural and human-influenced environmental conditions on their frequency and size (Van Den Eeckhaut et al., 2017; Tanyas et al., 2018; Maki Mateso et al., 2023). To assess to what extent the presence of terraces may affect the sizes of our landslides, we therefore fitted these distributions based on the mapped landslide extents and following the procedure of

Malamud et al. (2004). First, we looked at the probability-size distribution for each of the three landslide events separately. Next, we looked at the probability-size distribution for landslides in terraced and non-terraced areas separately. Finally, for the 2020 event alone, we looked at distribution in terraced and non-terraced areas separately.

3. Results

3.1. Landsides inventories

Our inventory contains 4,687 landslides in total. This number corresponds to an extra 2,222 landslides compared to previous inventories compiled by Deijns et al. (2022), Depicker et al. (2021a), and Dewitte et al. (2021). Most of these landslides are shallow (up to a few meters deep) avalanches and slides (Hungr et al., 2014; Dewitte et al., 2021; Deijns et al., 2024) (**Fig.** 3). The materials involved were mainly soil and debris. The total area of all the landslides covers approximately 1% of the areas of the three clustered zones. The largest landslide-affected area is 0.30 km^2, while the smallest detected landslide is 5 m^2 and the median size is 522 m^2.

The 2020 landslide event was clearly the largest one, not only in terms of extent of the cluster zone, but also in terms of the number of landslides, the total landslide area and the number of landslides on terraces. This event's cluster zone also contains the largest area and proportion of (mostly radical) terraces. The 2016 event was the smallest in terms of landslide numbers, total affected area but also the area treated with terraces (**Fig. 3; Table 3**).

***Table 3*:** Overview of the inventoried landslides for the three mapped events. '#' stands for number.

Landslide event	Size of event cluster zone (km^2)	Total terraced area (km^2)	Radical terrace area (km^2)	Progressive area (km^2)	Non-terraced area (km^2)	Affected area (km^2)	Total # of landslides	# of landslides on terraces	# of landslides on radical terraces	# of landslides on progressive terraces	# of landslides on non-terraced areas
2020	735.9	73.6	66.2	7.4	662.3	7.2	2,222	709	670	39	1,513
2018	149	9.2	4.2	5	139.6	2.4	1428	50	22	28	1,378
2016	380	6	5.7	0.28	374.5	0.6	1,037	14	9	5	1,023
All	1,265	88.8	76.1	12.7	1,176.4	10.2	4,687	773	701	72	3,914

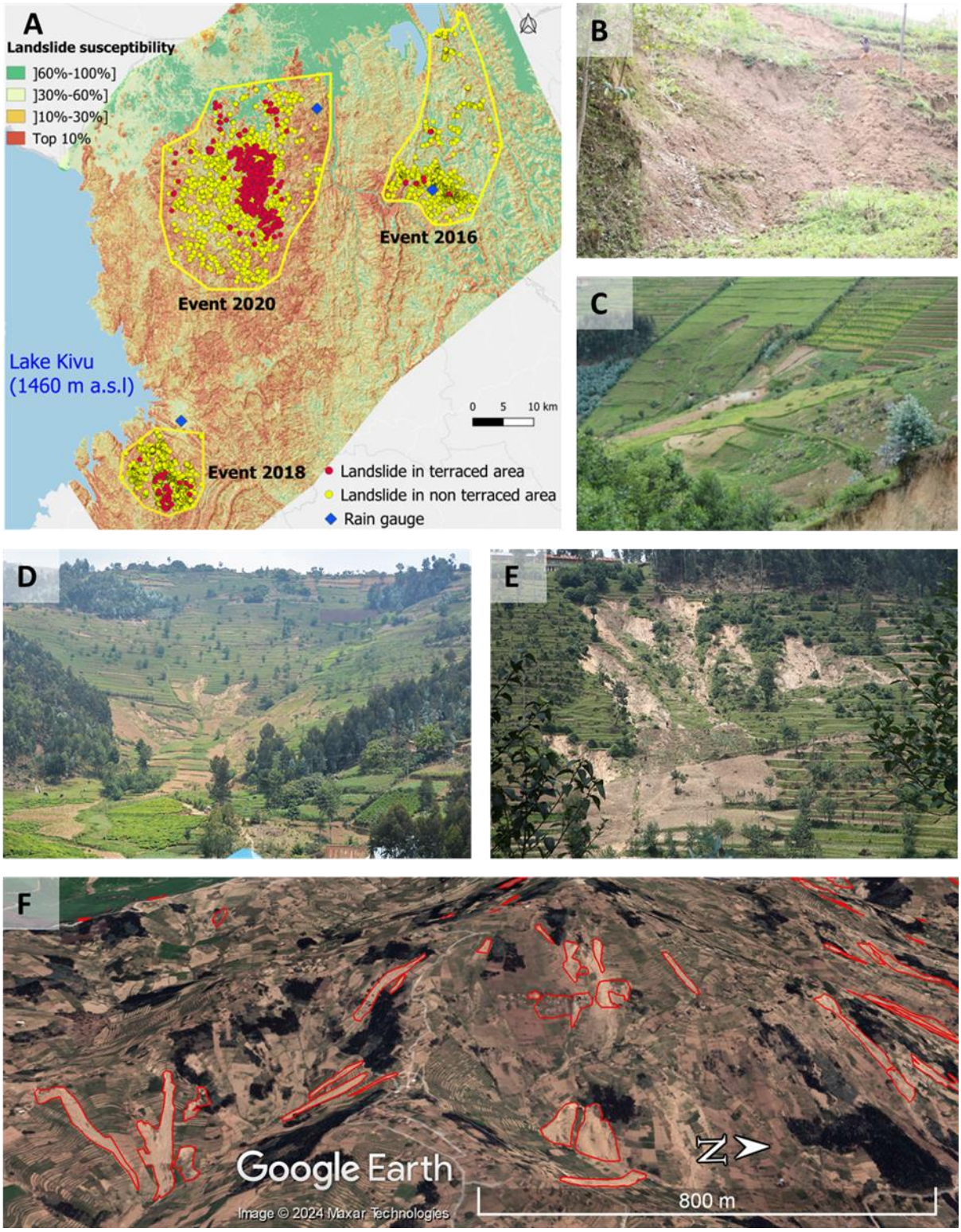

Fig. 3: Landslide inventory and some examples. **(A)** distribution of landslides triggered by the three events. The background shows the expected landslide susceptibility (Depicker et al., 2020). Four classes of susceptibility were provided as follows: the top 10% (here qualified as very high susceptibility), the 10%-30% (high susceptibility), the 30%-60% (moderate susceptibility), and the 60%-100% (low susceptibility). **(B)** Landside in a cultivated, non-terraced hillslope (picture taken in October 2020; 29°45'26.15"E, 1°35'23.92"S). **(C)** Landslides in progressive

terraces (picture taken in October 2020; 29°31’48.63”E, 1°44’36.923S). **(D)** and **(E)** Landslides in radical terraces (pictures taken in October 2020; **(D)**: 29°31’33.14”E, 1°40’10.71”S; **(E)**: 29°30’13.45”E, 1°38’32.83”S). **(F)** Several landsides of the landslide event of 2020 as mapped on an image of August 2020 from Google Earth (29°31'1.63"E, 1°45'18.32"S).

3.2. Effect of terracing on landslide occurrence

Considering all three event clusters together, agricultural terraces cover only around 7% of the study area (**Fig. 4**). Nonetheless, a disproportionally large amount of landslides that were mapped across these three events occurred in terraces. This is true in terms of frequency ratio, as well as in terms of odds ratios (**Fig. 5a**). For the three events combined, the odds ratio indicates that landslides were about three times as likely to occur in terraced areas as compared to non-terraced areas.

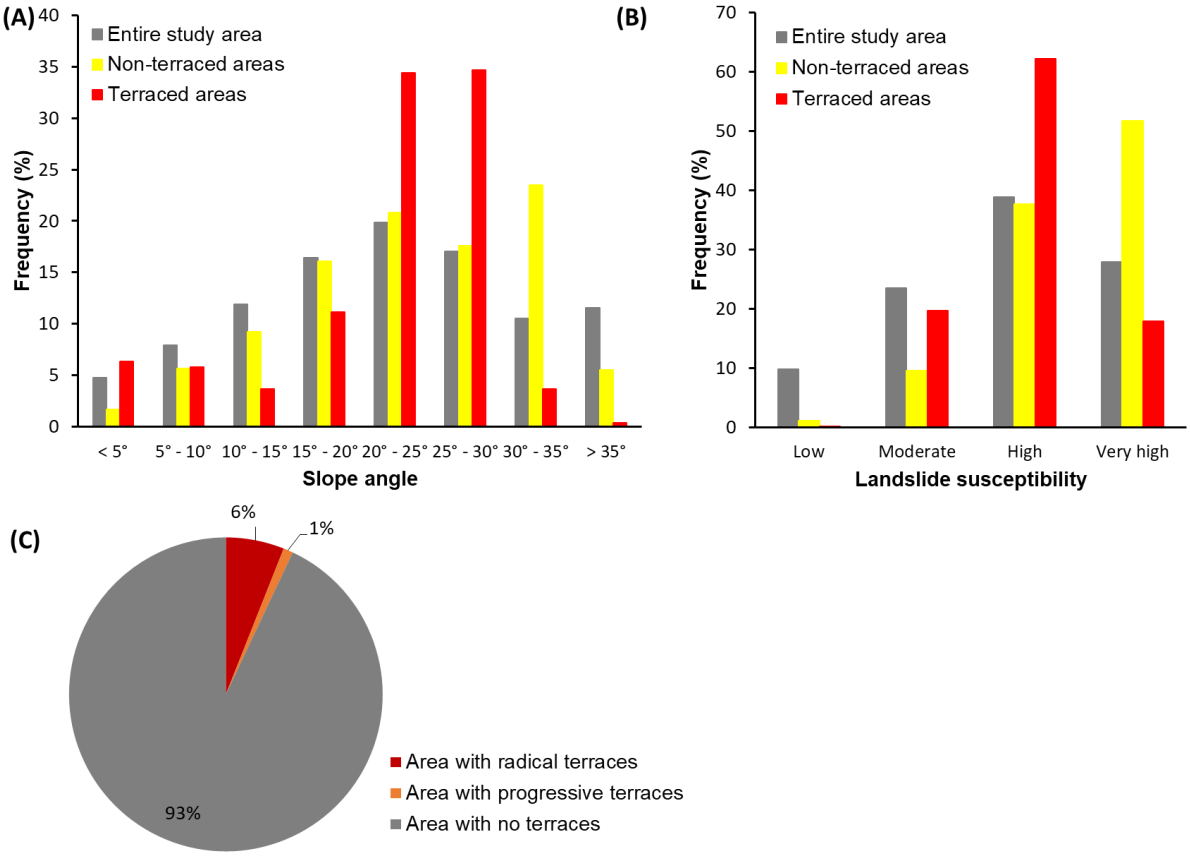

Fig. 4: Characterization of the three landslide events combined. **(A)** Frequency distributions of slope angles within the study area, subdivided in terraced and non-terraced areas. **(B)** Frequency distributions of landslide susceptibility classes within the study area (as defined by Depicker et al., 2020), subdivided in terraced and non-terraced areas. **(C)** Frequency distribution of areas with radical terraces, progressive terraces, or no terraces.

First, large contrasts exist between the three events. For the event of 2020, which was the overall largest event that occurred in an area with the highest proportion of terraces (**Table 3**), the odds ratio was 3.2 (**Fig. 5A**). Yet, for the 2018 event, the odds ratio was only 0.34, indicating that landslides were three times less likely to occur in terraces as compared to non-terraced areas. For the 2016 event, the odds ratio is close to one, suggesting no clear effect. However, with only ~1.6% of the area covered by terraces and only 14 landslides recorded in these terraces (**Table 3**), this value may be little representative.

Considering the landslide occurrence per slope angle class (**Fig. 5B**), landslide densities and frequency ratios generally increase with slope steepness. This holds for both terraced and non-terraced areas. Nevertheless, both terraced and non-terraced areas tend to show a different trend in terms of landslide occurrence, which is also reflected in the odds ratios. For relatively flat areas (< 15°), landslides were about 3.5 times more likely to occur in terraced as compared to non-terraced areas. However, given the overall low frequency of landslides in this slope class (**Fig. 4A**), this result should be interpreted with caution. For moderate slope classes, the odds ratio starts around 1.5 (15°-20°) but then strongly increases to nearly six (25°-30°). However, for steeper slope classes (> 30°), the odds ratio drops below one. While many landslides fall within this slope class, the extent of terraces in areas steeper than 30° is limited (**Fig. 4A**). Overall, these results indicate that the relatively higher occurrence of landslides in terraced areas mainly occurs in areas with a gentle to moderately steep slopes (< 30°).

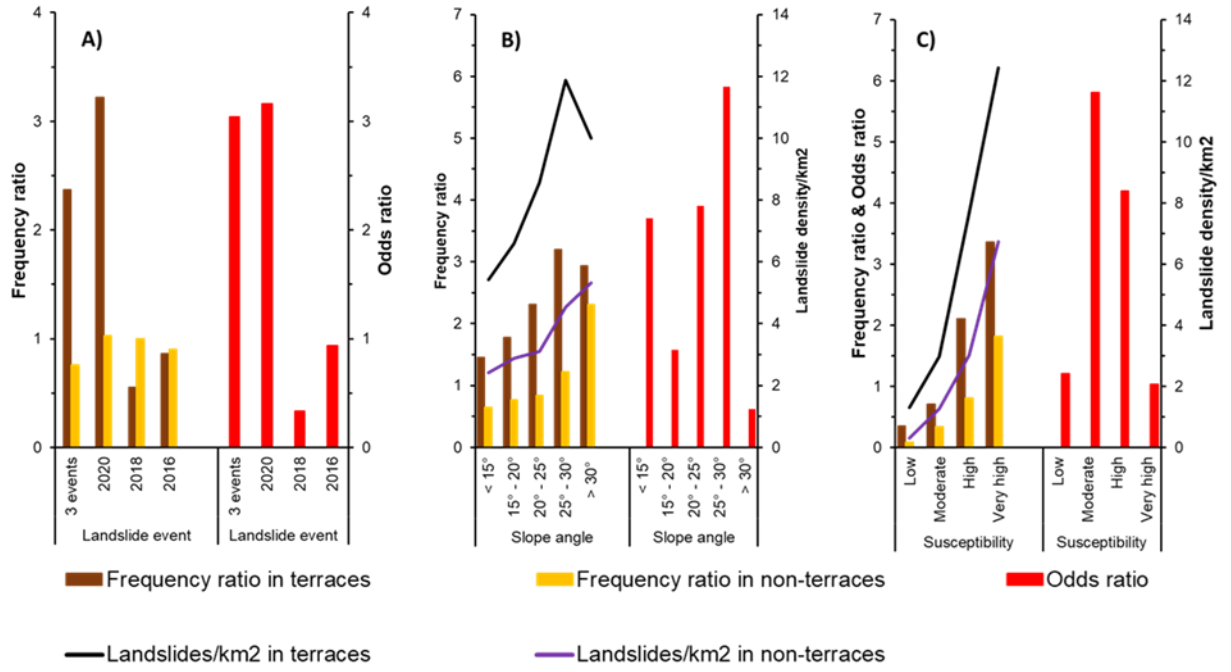

Fig. 5: Frequency ratios, odds ratios, and landslide frequencies for the three landslide events combined: **(A)** per landslide event; **(B)** three events combined, subdivisions per slope class; and **(C)** for the three events combined, subdivided per landslide susceptibility class.

Comparable results can be found when considering landslide susceptibility (**Fig. 5C**). As can be expected, landslide frequency ratios and densities strongly increase with the susceptibility class in both terraced and non-terraced areas. However, the contrast between both is especially pronounced for areas with a moderate to high susceptibility (with odds ratios ranging between 4 and 6). In areas with a very high susceptibility, the odds ratio lies close to one. The same holds for areas with a low susceptibility. Yet, in this case, also the number of landslides is overall very limited (**Fig. 4B**).

Fig. 6 presents a further exploration of these trends, separated per event. For the 2020 event, results are relatively similar to the overall analyses (**Fig. 5**), which is to be expected as this event also contributes the largest number of landslides and terraced areas to the combined dataset (**Table 3; Fig. 3**). Again, the effect of terracing on landslide occurrence is largest for weak to moderate slopes, with odds ratios dropping to around 1 for slopes steeper than 25° (**Fig. 6A**). In terms of landslide susceptibility, the odds ratios for landslides on terraced versus non-terraced areas are

clearly higher for moderately to highly susceptible zones (**Fig. 6D**). Yet, for areas with a low and very high susceptibility, the difference is clearly much less pronounced.

Clearly different patterns emerge for the 2018 event. Frequency ratios generally do not increase greatly with slope angle, except for slopes steeper than 30° (**Fig. 6B**). Across all these slope classes, frequency ratios and landslide densities are lower in terraced than in unterraced areas, resulting in odds ratios below one. For this event, no landslides occurred in terraced areas with a low to moderate susceptibility (**Fig. 6E**). Yet, for areas with high to very high susceptibilities odds ratios are also clearly below 1. For the 2016 event, landslide frequencies and densities generally increase with both slope angle (**Fig. 6C**) and landslide susceptibility (**Fig. 6F**). As for the 2020 event, odds ratios are generally larger than one for areas with a moderate slope angle (15°-20°), but drop for slopes >30° (**Fig. 6C**). Likewise, odds ratios are higher for areas with a moderate susceptibility (**Fig. 6F**). However, given the limited extent of terraced areas in this event zone and since only 14 landslides were mapped in these terraces (**Table 3**), these results should be interpreted with caution.

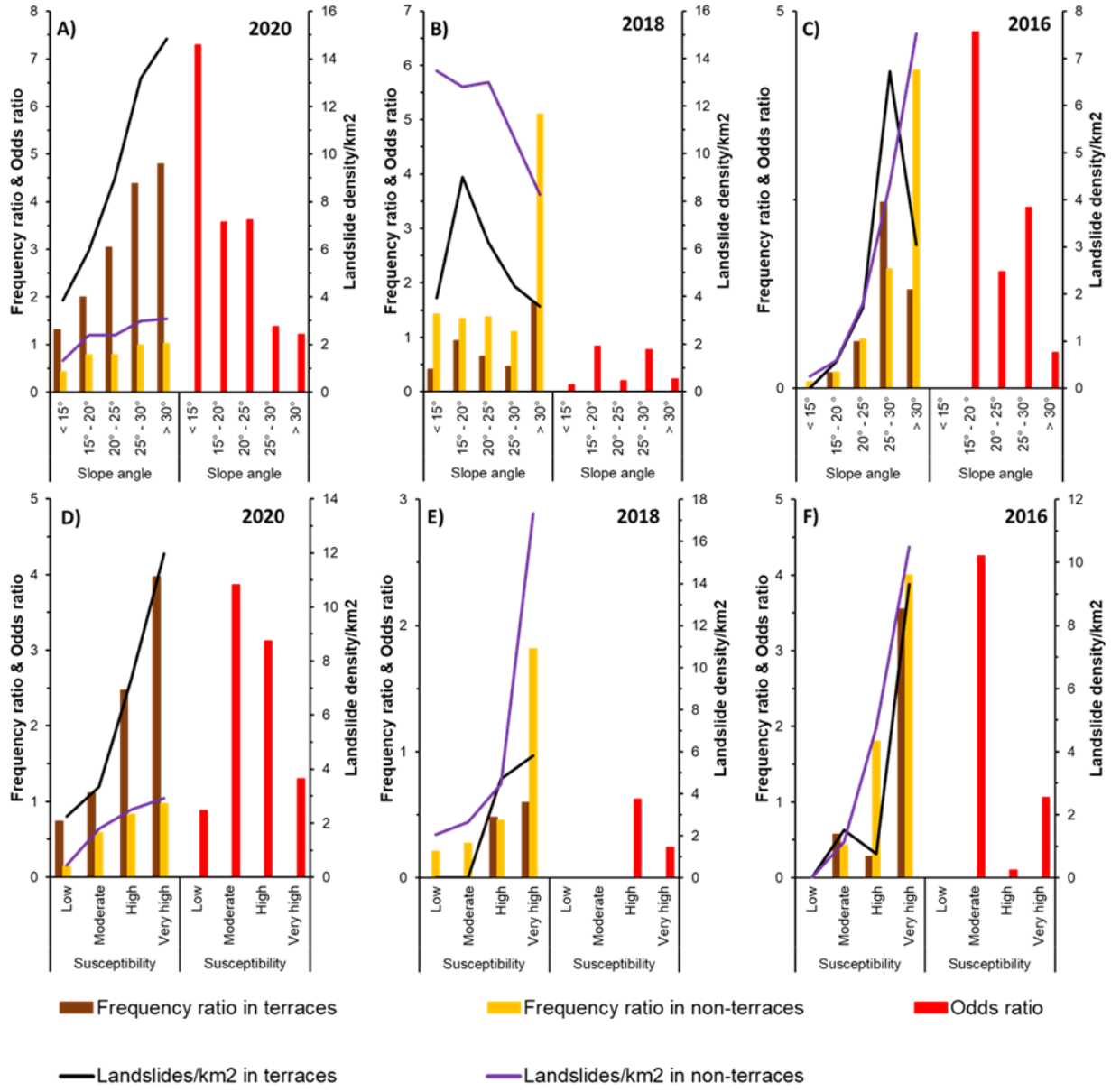

Fig. 6: Frequency ratio, landslide density, and odds ratios of landslides on terraced versus non-terraced areas for the three separate events. **(A)**, **(B)**, and **(C)** show these metrics per slope class for respectively the 2020, 2018 and 2016 events. **(D)**, **(E)**, and **(F)** shows the same metrics per class of landslide susceptibility for respectively the 2020, 2018 and 2016 events.

3.3. Potential effect of terraces on landslide susceptibility

The earlier developed regional landslide susceptibility model by Depicker et al. (2020) performs overall relatively weakly in predicting the source locations of the landslides triggered by the rainfall events (**Fig. 7**). Constructing a Receiver Operation Characteristic (ROC) Curve based on this model for the three events combined results in an Area Under the Curve (AUC) of only 0.62

(**Fig. 7a**). Especially for the 2020 event, the model could not well discriminate the landslide from non-landslide areas (**Fig. 7b**). For the 2018 and 2016 events, the model performed better with AUC values of respectively 0.75 and 0.82.

When we add the presence (1) or absence (0) of terraces as a dummy variable to the existing model by Depicker et al. (2020), the predictive accuracy of landslide locations triggered by the events seems to be clearly improved (**Fig. 7a**). This is particularly so for the 2020 event, where including this dummy variable increases the AUC value to 0.72. For the other two events, adding this dummy variable led only to marginal improvements (with changes in AUC value of less than 0.01).

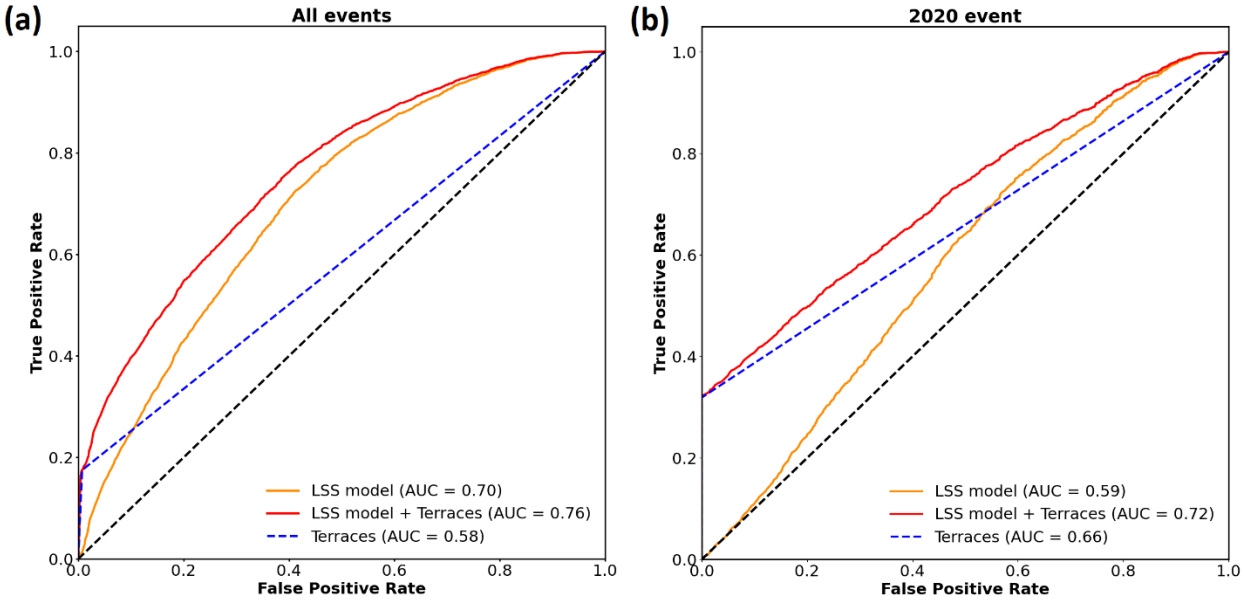

Fig. 7: Receiver Operation Characteristic (ROC) curves for the landslide susceptibility (LSS) model of Depicker et al. (2020), for all three events **(a)** and for the 2020 event **(b)**. Yellow lines show the ROC curve based on the original model with the Area Under the Curve (AUC) value indicated in the legend. Blue lines show the ROC curve when only a dummy variable indicating the presence or absence terraces would be used. Red lines show the ROC curve based on the LSS model plus this dummy variable.

3.4. Size-frequency distribution

All three events show a size-frequency distribution (**Fig. 8A**) that matches relatively well with the gamma distribution proposed by Malamud et al. (2004). Yet, with landslides of around 100 to 1000 m² occurring most frequently, the 'rollover' in size-frequency distribution occurs at slightly smaller sizes than the theoretical distribution would suggests. This indicates that a relatively high number of small landslides occurred. Overall, the three events show different size-frequency

distributions (Kruskal-Wallis test $p < 0.000$). Moreover, the 2020 event tends to have a higher frequency of larger landslides (> 10,000 m²; **Fig. 8A**) and greater variability.

Considered over the three events combined, landslides in non-terraced areas tend to have a slightly higher size-frequency distribution than landslides in terraces (**Fig. 8B**). The same holds for the 2020 event, indicating that landslides occurring in terraces tend to be typically slightly smaller (**Fig. 8C**). For the other two events, the number of landslides occurring in terraces was too low to fit a separate size-frequency distribution (**Table 3**).

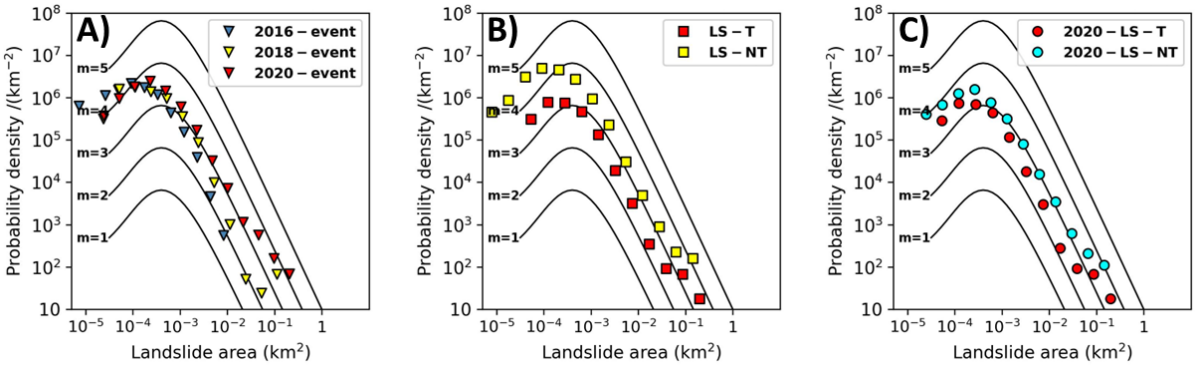

Fig. 8: Landslide size-frequency distribution for **(A)** the three mapped landslide events; **(B)** all mapped landslides across the three events that occurred in terraced and non-terraced areas; and **(C)** the 2020 landslide event, subdivided for terraced and non-terraced areas. LS-T: landslides in terraced areas, LS-NT: Landslides in non-terraced areas. The theoretical distributions for various landslide-event magnitudes (m) proposed by Malamud et al. (2004) are represented with black curves. An inventory that that would contain 100 landslides is represented by m = 2; 1000 landslides by m = 3, etc.

4. Discussion

4.1. A highly landslide-prone region

Several earlier studies already highlighted the significance and dangers of rainfall-triggered landsliding in tropical hilly and mountainous regions like NW Rwanda (e.g., Monsieurs et al., 2018; Depicker et al., 2020; Dewitte et al., 2021; Depicker et al., 2021b; Deijns et al., 2022). With over 4,600 landslides mapped across the three studied events, our results further demonstrate this importance (**Fig. 3; Table 3**). All three events occurred in May, which corresponds to the end of the second rainy peak of the wet season and is generally the period with the highest landslide activity in the region (Monsieurs et al., 2018). It is at such moments, when soil moisture contents have already built up to very high levels, that large but not necessarily exceptional rainfall events (**Table 1**) can have devastating impacts (Monsieurs et al., 2018a).

Most of the landslides mapped were shallow landslides of the avalanche or slide type affecting soil and debris material; i.e., two types of landslide processes of different mobility behaviors that frequently interact and that are commonly associated with intense short-duration rainfall events (Hungr et al., 2014). This was clear from the interpretation of the Google Earth imagery and further confirmed by our field surveys. It also corresponds to the findings of earlier research in the region (e.g., Monsieurs et al., 2018; Depicker et al., 2020, 2021a; Dewitte et al., 2021; Deijns et al., 2024) and other places in the African Rift for example (Niyokwiringirwa et al., 2024). Our analyses (**Fig. 8**) further indicate that the observed landslides are often relatively small, with a rollover in size-frequency distribution occurring around 100 m². This is likely attributable to the often relatively shallow depth of the shear plane (Depicker et al., 2021a). Remarkably, landslides mapped on terraces tend to be slightly smaller than those mapped in non-terraced areas (**Fig. 8B, 8C**). This could indicate that some of the observed landslides in terraces may in fact be caused by local oversteepening and/or collapse and/or overloading at terrace risers (Critchley and Bruijnzeel, 1995; Tarolli et al., 2014).

4.2. Contrasts between the events

Considered over the three events combined, landslides appear to be around three times as likely to occur in terraced areas than in non-terraced areas (**Fig. 5**). This is in line with the findings of earlier studies in other regions (Crosta et al., 2003; Turkelboom et al., 2008; Cevasco et al., 2013; Agnoletti et al., 2018). Yet, our results provide some of the first quantitative evidence for this from a tropical region in Africa (Kitutu et al., 2011).

Nevertheless, our results also demonstrate the complexity of rainfall-triggered landsliding in terraced tropical landscapes. For example, of the three events studied, only the 2020 event showed a very clear impact of terracing on landslide occurrence (**Fig. 5A**). Noteworthily, this was also the most significant event, both in terms of landslides triggered and terraced areas (**Table 3**). For the 2018 event, however, landslides tended to occur less frequently in terraced than on non-terraced areas, while no clear terrace-effect could be detected for the 2016 event. Yet, for this last event, also the extent of terraces in the affected area was very limited (**Table 3**).

Several factors and mechanisms may help explaining why landslides occurred much more frequently in terraces during the 2020 event. First, as already indicated above, the construction of terraces may lead to oversteepening and overloading. This, in combination with the local heterogeneities in soil strength that the construction of terraces may induce (Crosta et al., 2003; Milledge et al., 2014) can result in overall lower slope stabilities. Second, terraces can significantly alter the water balance of hillslopes. By design, terraces aim to limit runoff and promote infiltration, which can lead to soil saturation and increased failure risks (Crosta et al., 2003; Brown et al., 2021). This is especially so near the riser of terraces where the local hillslope is steepest, much of the soil water accumulates and the increased soil thickness is potentially larger than the rooting depth of the vegetation (Arnáez et al., 2015; Pijl et al., 2021).

Nevertheless, it remains unclear why the 2018 event showed overall lower odd ratios for landslides triggered on terraces as compared to non-terraces (**Fig. 5; 6**). Both the 2018 and 2020 events were clearly significant in scale (**Fig. 3**) and were associated with rainfall amounts that look similar (**Table 1**). In addition, the terraces are all being used and relatively well-maintained in both areas; hence, terrace abandonment cannot be invoked as a cause of increased landslide incidence in the 2020 event (Crosta et al., 2003; Pepe et al., 2019).

One element that may play a role is the underlying lithology and the regolith and soil characteristics that result from this. The area affected by the 2018 event is mainly dominated by shales, micaschists, and schists, which can be expected to mainly result in clayey weathering products (**Table 2**). The 2020-event area, on the other hand, is mainly characterized by pegmatite, granite and gneiss (**Table 2**), which often weather into sandier soil types. As sandy soils tend to be more permeable and less cohesive (Das, 2010: Thomas et al., 2020), it may be possible that the impact of terraces on landsliding is more pronounced on sandy hillslopes. Terraces have the capacity to ameliorate soil moisture content by altering the hydrological dynamics of the soil. On sandy hillslopes, this phenomenon might reduce the shear strength of the soil, therefore increasing its potential to instability (Sasahara and Sakai, 2014; Terajima et al., 2014). Yet, further analyses revealed no clearly interpretable differences in odds ratios when grouping landslide occurrence per lithology. This may be attributable to the lack of sufficiently detailed soil and lithology maps, as well as to the role of other confounding factors. For example, small-scale variations in soil

characteristics will also affect land use and vegetation patterns, which in turn may influence hillslope hydrology and landsliding. Likewise, differences in landslide occurrence within the affected areas may be strongly influenced by local variations in rainfall conditions during the event (Monsieurs et al., 2018; 2019). However, also here, we lacked sufficiently detailed information to further analyze this. Another potentially important element is that relatively more progressive terraces occur in the area affected by 2018 event, while the 2020 event mainly occurred in an area with radical terraces (**Table 3**). Given their much more limited effect on slope morphology (**Fig. 2**), it may be expected that progressive terraces will have a smaller impact on landslide dynamics. Nonetheless, no strong contrasts in frequency ratios could be observed for both terrace groups. Furthermore, this would only explain why we would see a less clear impact of terraces; not why relatively less landslides occurred in terraces for the 2018 event.

As such, our findings also indicate the limitations of geostatistical analyses to understand the effect of terracing on rainfall-triggered landsliding. Despite their added value, such broadscale analyses are best also complemented with more detailed field-based and process-oriented research. In particular, actual observations on the relation between soil moisture in relation to rainfall, soil characteristics and land use/management practices would provide an important added value here. Yet, despite recent advancements (e.g., Thomas et al., 2019, 2020; Wicki et al., 2021; Uwihirwe et al., 2022), such observations remain very rare for the tropical Global South; in particular when it comes to the role of terraces (Sidle et al., 2006; Lewis et al., 2015; Wei et al., 2016).

4.3. Terraces and landslide susceptibility

Despite the difficulties to fully explain the contrasts in results across the three events, our findings clearly demonstrate that the increased likelihood of landslides in terraced areas mainly occurs on hillslopes with a moderate to high landslide susceptibility. The effect is much less pronounced for areas already having a very high susceptibility (**Fig. 5C**). This is certainly the case for the 2020 event (**Fig. 6D**), but also for the other two events, odds ratios tend to be relatively lower in very susceptible areas (**Fig. 6E, 6F**). Similarly, odd ratios tend to be higher for moderate to steep slopes (15-30°), but lower for very steep slopes (> 30°; **Fig. 5B**). To some extent, this may be linked to the fact that terraces are also much less frequently constructed on very steep hillslopes (**Fig. 4**), i.e. on the slopes that are characterized by the highest landslide susceptibility (Depicker et al.,

2020). Even with terraces, these slopes often remain less suitable for cultivation. This is in confirmation with Water for Growth Rwanda (2018) who reported that in Rwanda, they construct agricultural terraces on hillslopes with a specific slope angle, typically below 35°. The slopes in the class > 30° coincide with the presence of threshold hillslopes; i.e. slope angle conditions that are associated with a clear increase of landslide activity (Depicker et al., 2021a). Moreover, it is mainly on these already susceptible but not extremely landslide-prone hillslopes that terraces can be expected to make an important difference. It is mainly there that small changes in shear stress or strength, for example due to increased soil moisture contents or local oversteepening, can tip the balance towards unstable hillslope conditions (e.g., Schilirò et al., 2018).

This also has important implications for landslide prediction. Earlier work already indicated that uncertainties on predicted landslide occurrences are overall largest in areas with a moderate estimated susceptibility (e.g., Rossi et al., 2010; Broeckx et al., 2018). While the most and least susceptible areas are often easy to determine, it is in this range of moderately susceptible hillslopes that small changes in hillslope conditions can make a significant difference. This is also demonstrated by the comparison of our landslide inventories with the regional landslide susceptibility map of Depicker et al. (2020) (**Fig. 7**). While this map could somewhat predict where landslides were to be expected in the three impact zones, the performance is overall much lower than the original validation result (with a validation AUC of 0.92; Depicker et al., 2020). This is especially so for the 2020 event, where the map performs only slightly better than a random model. Several elements may explain this. For example, the model of Depicker et al. (2020) was trained at the regional scale level on a variety of landslides types in different geomorphological and lithological contexts, occurring over much longer periods that faced different climate conditions (Dewitte et al., 2021). The model of Depicker et al. (2020) is also not accounting for particular soil and conservation practices as land use controlling factor. Furthermore, as already indicated above, landslide patterns within the affected zone were likely greatly influenced by local rainfall conditions. The exact rainfall patterns were unknown and uncounted for by this susceptibility model. Yet, it is known that such variations can be very significant in tropical environments (e.g., Monsieurs et al., 2017; 2018).

Nevertheless, our results indicate that landslide susceptibility models in this region could greatly improve their predictive performance by accounting for the effect of terraces. This is especially the case for the 2020 event (**Fig. 7b**), where a simple dummy variable indicating the presence or absence of terraces was already better in discriminating in landslide from non-landslide areas than the model by Depicker et al. (2020). Yet, as in many regions, systematic data on the presence and characteristics of terraces are lacking for this part of the world.

4.4. Implication for land management and soil and water conservation strategy

Given that terracing mainly occurs on hillslopes with a moderate to high landslide susceptibility (**Fig. 4**), our findings also illustrate the difficulty of developing appropriate land management strategies in mountainous and intensely cultivated tropical regions like NW Rwanda. Given the high slope gradient of many cultivated plots (e.g., **Fig. 3**), terraces are often a requirement for cultivation and can be expected to be an effective strategy to reduce soil erosion (e.g., Ebabu et al., 2022). Yet, these terraces can in some situations significantly increase the landslide risk. As our results illustrate, these risks remain difficult to predict. For example, they are not necessarily only the most susceptible zones that should be safeguarded from terracing. Furthermore, not every rainfall-triggered landsliding event will result in higher landslide rates on terraces. Nonetheless, as the results for the 2020 event demonstrate (**Fig. 5, 7**), terraces can in some cases drastically increase the occurrence of landsliding.

Various studies already indicated that especially the abandonment and poor maintenance of terrace can result in elevated landslide risks (e.g., Cammeraat, 2004; Koulouri and Giourga, 2007; Romero Díaz et al., 2007; Lesschen et al., 2008; García-Ruiz et al., 2013; LaFevor, 2014; Arnáez et al., 2015; Londoño et al., 2017; Chen et al., 2023). Yet, it is important to note that the terraces in our study area were not abandoned and overall well-maintained. In addition, the rainfall events associated with our events were clearly significant, but, as showed by Monsieurs et al. (2018a) not exceptional (**Table 1**). This further indicates that the higher occurrence of landslides on terraces cannot be attributed to extreme circumstances or poor maintenance, but intrinsically linked to the presence of terraces themselves.

As such, under the high population pressure that Rwanda is facing, choosing between the potential for cultivation, reduced erosion risks, or reduced landslide risks can become a very difficult exercise. The relevance of making this tradeoff correctly and of finding ways to further minimize landslide risks will likely only increase in the future (Depicker et al., 2021b). While agricultural terraces have already been constructed at a large scale in NW Rwanda (e.g., Bizoza, 2011; Uwacu et al., 2021), their extent will likely continue to increase in the near future.

5. Conclusion

Based on the analyses of three rainfall-triggered landslide events in NW Rwanda, we showed that terracing can overall lead, in this specific case, to around three times more landslides as compared to non-terraced areas. While this finding is overall in line with findings from other studies, this work is to our knowledge the first, large-scale quantitative demonstration of this effect for tropical Africa; a region facing enormous land use pressure and likely an important future increase in terraces.

Yet, our work also demonstrates the large variability and complexity of assessing landslide occurrence in relation to terracing. First, the largest 2020 landside event, which also features > 80% of the terraced areas of our study, clearly demonstrated the impact of terracing on landsliding. For the other two events, no (2016 event) or even a negative (2018 event) effect was observed. Yet, the much lower extent of terraces in these two affected regions makes it difficult to draw hard statistically supported conclusions from this. Second, increased landsliding due to terracing was mainly observed on hillslopes with a moderate to high landslide susceptibility and less so on very susceptible slopes. Not only are these moderately susceptible slopes more frequently terraced, it is likely also here that changes in hillslope hydrology induced by the terraces have the largest effect. Third, while more frequent, landslides occurring in terraces tend to be slightly smaller.

These findings have important implications for land management and soil and water conservation strategy, as they demonstrate that finding a tradeoff between allowing agriculture, reducing soil erosion and reducing landslide risks can present a very difficult exercises. Our results open promising perspectives here as they demonstrate that incorporating the presence of terraces in

landslide susceptibility models can lead to more accurate predictions. Nonetheless, geo-statistical analyses as presented in this work also come with limitations. More research is therefore recommended to further disentangle the relationships between terracing and landsliding, particularly in such tropical environments where knowledge on soil and climate remains limited. Especially field-based observations on the relationship between rainfall patterns and soil moisture under contrasting land management practices and soil types can likely shed more light on the complexities revealed by our results.

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