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Documenting five years of landsliding after the 2005 Kashmir earthquake, using repeat photography

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ABSTRACT

The 8 October 2005 Kashmir earthquake triggered thousands of landslides at different scales through the Hazara–Kashmir region of northern Pakistan. A landslide inventory was prepared within a few months after the earthquake, which included detailed photographs and studies of landslides at 164 locations. Photographs were retaken in 2006 at all the 2005 locations and at selected 68 landslide locations in 2007. In 2010, 123 of the 2005 landslide locations in the inventory were reexamined and photographed again. Existing literature predicted that extensive landsliding, particularly under wet conditions, was likely to occur in the region in the years immediately following the earthquake. Surprisingly, the repeat studies revealed that the total landslide area increased only slightly over the five-year period of study, even given a particularly heavy monsoon rainfall season in 2006, with 46% of the locations showing little or no increase and 10% showing a noticeable increase in landsliding; in 44% of the locations vegetation growth was significant or complete within the exposed landslide slip area. Many of the new or reactivated failures occurred along roads and rivers, particularly along steeper slopes. We conclude that the landscape returned to equilibrium within only a few years after the earthquake. Nevertheless, a potential for future slope instability and landsliding in the region still exists. Hence continuation of landslide monitoring and risk assessment is still important for hazard mitigation in this region.

1. Introduction

On 8 October 2005 at 8:50 a.m. local time (03:50 UTC), northern Pakistan experienced one of the most destructive earthquakes in its history. The M_w 7.6 (with intensities of up to X–XI) earthquake had its epicenter located at 34.493° N./73.629° E., 20 km NE of Muzaffarabad in Azad Kashmir, with a focal depth of ~26 km (USGS, 2012; Fig. 1). An area of about 30,000 km^2, mainly between the cities of Balakot and Bagh, in the district of Khyber-Pakhtunkhwa [KPK] and Azad Kashmir (formerly North West Frontier Province) was affected resulting in >73,000 fatalities, >130,000 injuries, and >611,000 homes destroyed or partially damaged resulting in >3 million homeless people (ERRA, 2010a,b). The cities of Balakot and Muzaffarabad experienced major destruction with 90% and 80% of the buildings destroyed, respectively; and some city areas were totally destroyed (ERRA, 2006). Both cities reported some of the highest fatality rates in Kashmir. The high number of fatalities and casualties was mainly the result of building collapse (ERRA, 2010a,b).

Earthquake-triggered landsliding represents a dangerous natural hazard that causes significant damage to property and infrastructure, injury, and loss of life. Earthquake-triggered landslides may also dam drainages to form lakes that constitute a secondary hazard because of their potential to burst and create catastrophic floods. The 8 October 2005 earthquake triggered thousands of landslides throughout the affected region, and some of them were directly responsible for human casualties. The Hattian Bala landslide was the most disastrous, destroying three villages and killing ~1000 people (Harp and Crone, 2006; Dunning et al., 2007; Owen et al., 2008). In the Jhelum valley, landslides killed ~250 people in Pahl and 30 people in Bandhi Tanholia; 98 houses were buried under a landslide in Jabla (Petley et al., 2006). The earthquake not only reactivated existing landslides but also triggered new landslides, particularly in areas close to the earthquake fault.

To assess the causal factors, we have implemented a long-term study of past, present, and future landsliding in Azad Kashmir (Kamp et al., 2008, 2010; Owen et al., 2008; Khattak et al., 2010). Here, we present the results from the fourth field campaign undertaken in 2010 and from the overall analysis of landsliding between 2005 and 2010, building on our work presented in Khattak et al. (2010). Our main conclusion is that the hazard posed by future landsliding has generally been overestimated in recent literature. In essence, the landscape returned to its geomorphic equilibrium within a few years after the earthquake, possibly because most of the landslides

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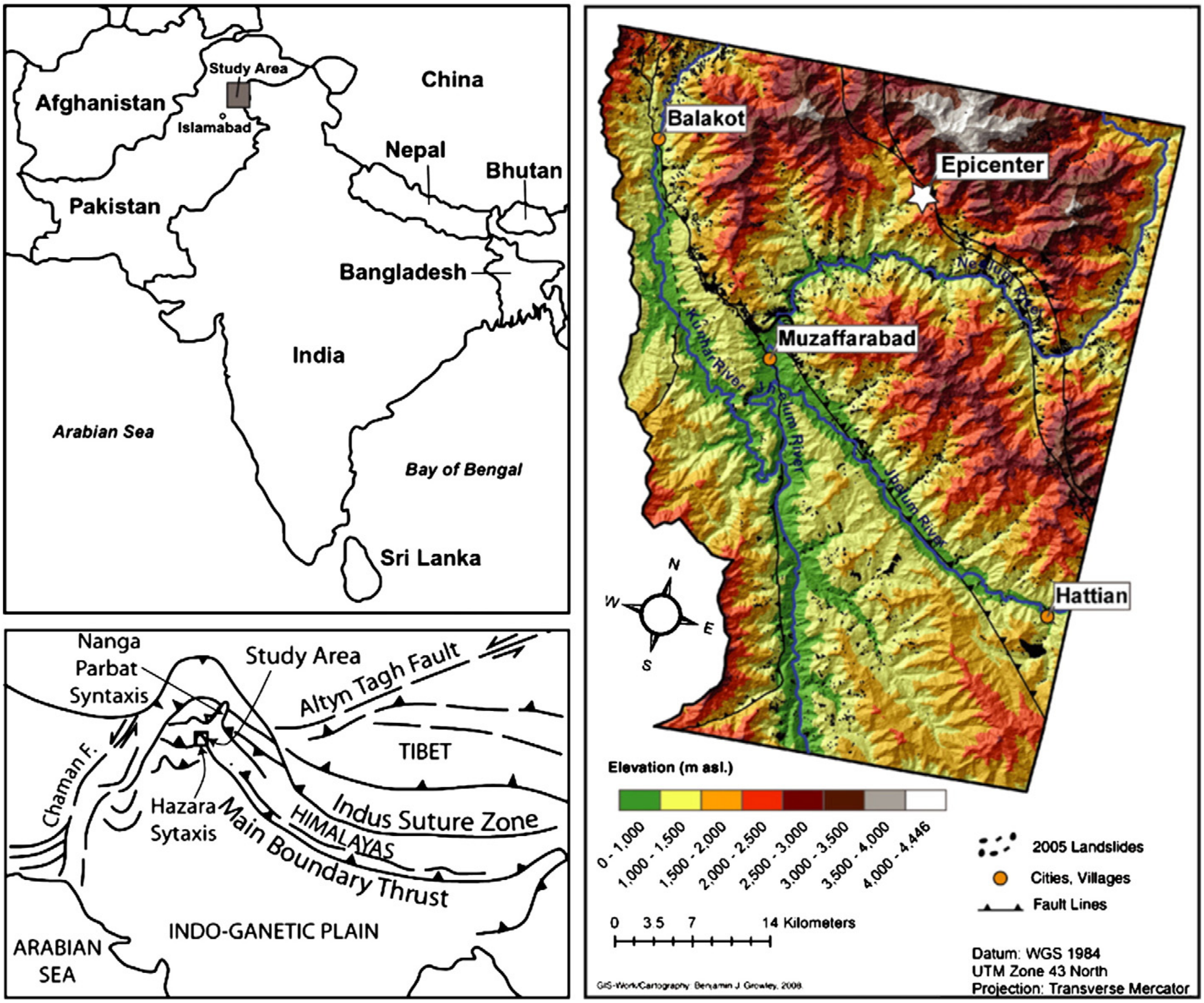

Fig. 1. The study area (2550 km^2) in Kashmir, northern Pakistan. The epicenter lies ~10 km NE of Muzaffarabad, the district capital of the state of Azad Jammu and Kashmir in northern Pakistan. The right map displays parts of the Kashmir Boundary Thrust (KBT) between Balakot and Hattian (adapted from Kamp et al., 2008).

were a shallow type and because of rapid growth of vegetation that helped stabilize the slopes.

2. Background

Landslides can have a direct or indirect impact on human lives and properties; hence, the literature on seismic landslides is extensive (e.g., Keefer, 1984, 1994, 1998; Owen et al., 1995; Harp and Jibson, 1996; Ravindran and Philip, 1999; Rodriguez et al., 1999; Luzi et al., 2000; Barnard et al., 2001; Antonini et al., 2002; Wang et al., 2003; Evans and Bent, 2004; Chen et al., 2006; Rathje et al., 2006; Hasegawa et al., 2009; Willige, 2010). Two kinds of seismically-induced ground failure exist: those such as liquefaction, consolidation subsidence, and some lateral spreading that are characteristic responses to earthquakes and those that include slumping, rock falls, and debris flows that might have occurred under nonseismic conditions but were exacerbated or enlarged by the tremors. In mountainous regions, earthquake-triggered landslides often occur in specific geologic–geomorphologic–anthropologic settings (Owen et al., 2008). Knowledge about such settings specific to individual regions and occurring landslide frequencies is crucial for reconstruction and rehabilitation.

The 8 October 2005 Kashmir earthquake initiated numerous investigations on landslide assessment and related hazard management (e.g., Harp and Crone, 2006; Petley et al., 2006; Vinod Kumar et al., 2006; Bulmer et al., 2007; Sato et al., 2007; Kamp et al., 2008, 2010; Owen et al., 2008; Champati Ray et al., 2009; Khattak et al., 2010; Peduzzi, 2010; Saba et al., 2010; Konagai and Sattar, 2012). Dunning et al. (2007) mapped 85 pre-earthquake, 73 co-seismic, and 21 post-seismic landslides from repeated satellite imagery in the Hattian Bala area where a landslide dammed the main valley and created two lakes. Sato et al. (2007) mapped 2424 landslides in the earthquake-affected region using SPOT 5 satellite images and showed that most of the landslides occurred on the hanging wall of the Kashmir Boundary Thrust (KBT). Sato et al. (2007) further noted that the majority (79%) of the landslides were <1 ha (<10^4 m^2) in size and that they were mostly rock falls and rockslides. This view was supported by Owen et al. (2008) who showed that 90% of the identified 1293 landslides in 164 locations in their study area were rock falls and debris falls with sizes ranging from single boulders to thousands of square meters; some of the landslides were very deep (tens of meters), whereas most were only shallow (a few meters). Owen et al. (2008) identified six specific geomorphic–geologic–anthropogenic landslide settings: (i) highly fractured carbonate rocks consisting of beds in the hanging wall of the Kashmir fault; (ii) tertiary silicate rocks along old drainages that cross through the Hazara–Kashmir syntaxis; (iii) slopes >50° consisting of Precambrian and lower Paleozoic rocks; (iv) slopes >50° of fluvially undercut Quaternary valley fills; (v) ridge spur crests; and (vi) failures associated with road cuts.

Kamp et al. (2008) analyzed ASTER images from 2005 and created landslide susceptibility maps for the earthquake region. Bedrock lithology and slope were identified as the two main factors for landsliding. Sixty-three percent of the landslides occurred in the Murree Formation that comprises sandstone, mudstone, and siltstone; and 31% of the landslides occurred on slopes between 25° and 35°. Kamp et al. (2008) showed that 67% of the landslides occurred in shrub and grassland and 20% in agricultural land, while <3% occurred under forest that covers ~45% of the study area. Kamp et al. (2008) noted that the areas around Muzaffarabad and Balakot were highly to very highly susceptible to future landsliding.

Kamp et al. (2010) compared 2001 and 2005 ASTER imagery and counted an increase of landslides from 369 in 2001 to 2252 in 2005, with the landslide area increasing from 8.2 km^2 to 61.1 km^2. Moreover, Kamp et al. (2010) concluded that the co-seismic landslide activity was 5 to 10 times greater than the background landslide activity, and they showed that much (75%) of the 2005 landsliding actually occurred in areas that had been considered highly to very highly susceptible to landsliding in 2001. Kamp et al. (2010) supported the view that in this landscape the equilibrium condition is one where ambient landsliding is continuously shaping the landscape in response to external factors.

Khattak et al. (2010) concluded that 80% of the revisited 68 locations from the 164 original locations of Owen et al. (2008) showed very little or no change between 2005 and 2007, 9% increased in size, and most occurred along roads or rivers and that 11% showed vegetation regrowth. Khattak et al. (2010) further found no evidence for a positive correlation of post-earthquake reactivated landslides and rainfall in the region because the landslide area increased only insignificantly (<10%) within the study area after the snowmelt season of 2006. Khattak et al. (2010) concluded that the landscape returned to pre-seismic conditions, its equilibrium state, within only a few years after the earthquake and that the extensive ongoing landsliding as predicted by Sudmeier-Rieux et al. (2007a,b), Kamp et al. (2008, 2010), and Owen et al. (2008) did not occur, although the landsliding still presented a hazard throughout the region.

Saba et al. (2010) produced a detailed spatiotemporal landslide inventory for a small area (36 km^2) around Muzaffarabad along the Bagh–Balakot fault to monitor changes in landsliding related to the monsoonal heavy rains. Five IKONOS and QuickBird satellite images (1 × 1 m ground resolution) from 2004 to 2008 were used to identify changes in landslide type and spatial distribution of slope failures after each monsoon season. Saba et al. (2010) showed that the number of landslides increased from 117 landslides in 2004 to 158 landslides in 2005 and to 391 landslides in 2006. After 2006, the landsliding decreased abruptly: in 2007 and 2008, the number of landslides increased by only 2 and 1, respectively. Saba et al. (2010) concluded that the area restabilized to its original condition prior to the earthquake within only two years.

In our new study, 123 landslide sites originally presented in Owen et al. (2008), which included 54 sites presented in Khattak et al. (2010), were revisited during the summer of 2010. The analyses included mapping, repeat photography, and assessment of the landslide activity for the Kashmir 2005 earthquake region between 2005 and 2010.

3. Study area

The study area is located in Azad Kashmir in northeastern Pakistan and includes the Kaghan, Neelum, and Jhelum River valleys and the cities of Balakot, Muzaffarabad, and Hattian Bala, covering an area of ~2550 km^2 (Fig. 1). The main valley floors are between ~500 and 2000 m above sea level (asl) with the highest peaks exceeding 4500 masl; Muzaffarabad is located at ~700 masl. The total population in the District of Muzaffarabad is ~750,000 with ~17,500 people residing within the boundary of the capital city Muzaffarabad (World Gazetteer, 2011).

The rocks in the study region date back to the middle Cretaceous (~90 Ma), when the Kohistan Island Arc collided with the southern margin of the Karakoram Plate, but the main orogenic phase began around 55 Ma and continued into the Oligocene (Hodges, 2000). Between 50 and 35 Ma, thrust stacking occurred leading to the formation of the Main Central Thrust (MCT) and to the Panjal and Nathiagali faults (Fraser et al., 2001). After 8 Ma, Cenozoic rocks of the northern Kohat and the Potwar plateaus were overlain by Precambrian and Phanerozoic rocks of the Attock-Cherat and Kala-Chitta ranges forming the Main Boundary Thrust (MBT; McDougall et al., 1993; Fig. 1). Subsequently, folding occurred along the Hazara–Kashmir syntaxis and Nanga Parbat syntaxis (Fraser et al., 2001). The 8 October 2005 earthquake ruptured the westernmost part of the Himalayan arc along the Kashmir Boundary Thrust (KBT) (known as the Murree fault in the study region) that extends from Balakot to Bagh on the western margin of the Hazara–Kashmir syntaxis (Baig, 2006; Bendick et al., 2007). Aftershocks were recorded within the Indus–Kohistan seismic zone on a blind thrust splaying from the MBT (Bendick et al., 2007).

The study area is influenced by the South Asian monsoon with monsoonal rains starting in early July and continuing until early September. The mean annual precipitation in the region is 1457 mm, of which 47% is monsoonal (WMO, 2012). Data from Balakot show that with a precipitation of 2284 mm the year 2006 was particularly wet, with half of the precipitation occurring during July and August; in the following years 2007 to 2010, precipitation was back to average values (Figs. 2 and 3). Months with significantly higher than average monthly precipitation were December and January of 2006 and 2008, February of 2010, June and July of 2008, and August of 2009, with June and July of 2008 being particularly wet (Figs. 3 and 4). Spring snow melt is another potential factor in contributing to landsliding. Unfortunately, no data are available on snow accumulation and/or snowmelt rates for the study area.

Houses are commonly built on the slopes adjoining the terraces prepared for agriculture and animal husbandry. Both natural slopes and terrace borders are potentially prone to failure during earthquakes or heavy rainfall events.

4. Data and methods

The original 2005 landslide inventory presented by Owen et al. (2008) included 1293 landslides at 164 locations in KPK and Azad

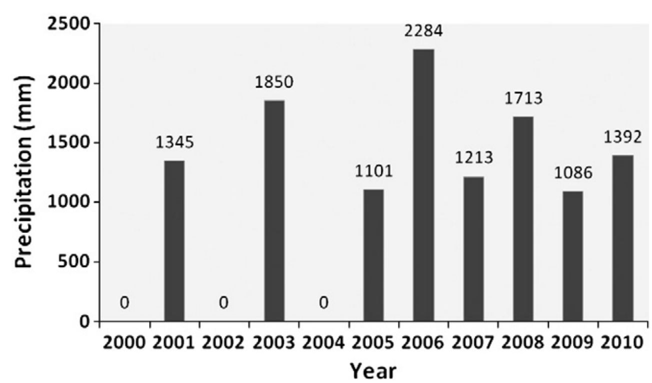

Fig. 2. Annual precipitation from 2000 to 2010 in Balakot (34°33′N./73°21′E.). (2000, 2002, and 2004: 0 = no data available).

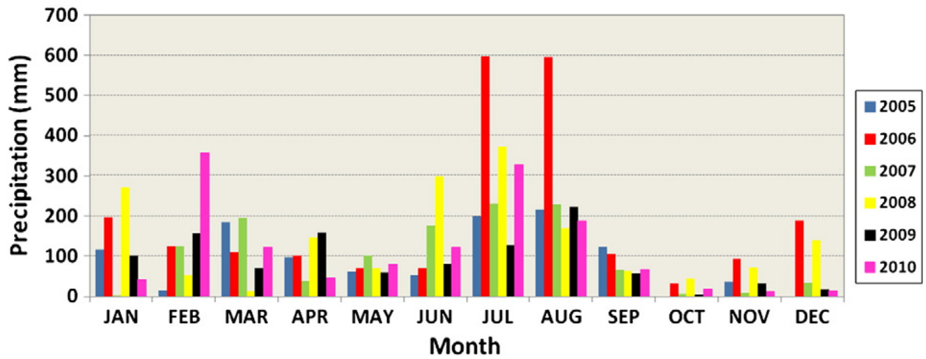

Fig. 3. Monthly precipitation from 2005 to 2010 in Balakot (34°33′N./73°21′E.).

Kashmir. In 2006 and 2007, 68 of the 2005 landslide locations were revisited and analyzed by Khattak et al. (2010). Extensive field work was undertaken in summer 2010 to collect new data and to undertake repeat photography to generate the fourth photographic data set for selected landslide locations: 123 of the Owen et al. (2008) sites including 54 of the Khattak et al. (2010) sites were revisited and rephotographed. The sites were selected based on their accessibility. Some of the 2005 sites no longer existed; for example, a lake outbreak flood washed away most of the landslides surrounding the Hattian Bala landslide.

The 2005, 2006, and 2007 photographic inventories provide information about photograph point location, photograph azimuth, and geologic–geomorphologic setting. In 2010, a photograph point was located in the field using its GPS waypoint from the inventories, and then identical photographs were taken. During the laboratory analyses, photographs from 2005 to 2007 were compared with the repeated photographs from 2010 at the same scale (accuracy of ± 1%) using on-screen digitizing and area measuring tools in Corel Draw 12 and AutoCAD 17.2. All sites that showed a change in extent of >2% in surface area, size, or shape were digitally analyzed. The sites with no change or minor change (<2%) were visually estimated for surface area change. Varnes' (1978) classification was used to describe landslide type. Additional information from field observations (e.g., lithology and road construction) and from external sources (e.g., number of aftershocks and new earthquakes) was also used when assessing the landslide activity (see also our supplementary landslide inventory).

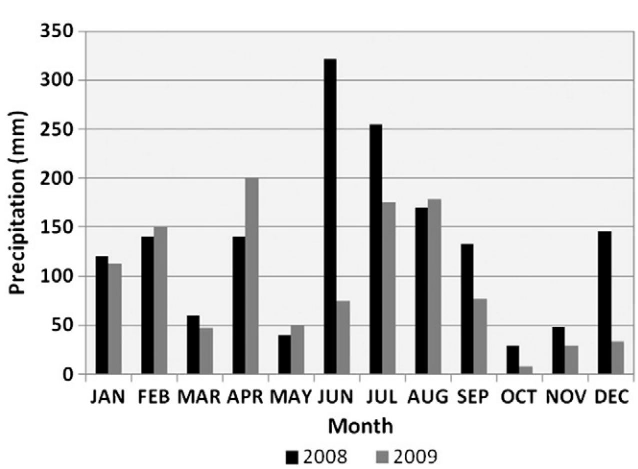

Fig. 4. Monthly precipitation from 2008 to 2009 in Muzaffarabad (34°21′N./73°28′E.).

5. Results

Our results show that the total number and size of the landslides decreased from 2005 to 2010. Although some sites remained active or increased in area, most remained unchanged (Table 1; Figs. 5–9):

- 2005 cf. 2007: of all revisited sites, 59% did not show any or very minimal change in landslide area, 32% showed noticeable vegetation growth on the landslide scars and masses, and 9% showed an increase in landslide surface area and remained active.
- 2007 cf. 2010: 56% of the sites showed no change or very minimal change in landslide area, 31% showed noticeable vegetation growth on the landslide scars and masses, and 13% showed an increase in landslide area and remained active.
- 2005 cf. 2010: 46% of the sites showed no change or very minimal change in landslide area, 44% showed noticeable vegetation growth on the landslide scars and masses, and 11% showed an increase in landslide area and remained active. Of all recovered sites, 7% showed 1–25%, 6% showed 26–50%, 19% showed 51–75%, 37% showed 76–99%, and 32% showed 100% increase in vegetation cover on the landslide scars and masses.
- 2005 cf. 2007 cf. 2010: The comparison of photographs from 2005, 2007, and 2010 shows that in some locations, although landsliding had ceased and vegetation growth had occurred on the landslide scars and masses by 2007, some landsliding reactivation occurred by 2010.

6. Discussion

While both Khattak et al. (2010) and our study document an increase in landslide area between 2005 and 2007 for only 9% of all sites, differences exist between the studies. Our study identified less (59%) sites with no change and more (32%) sites with vegetation growth. Reasons for such differences are probably the different sample sizes, accuracies of analyses, and software used to measure the changes in the repeated photographs. Khattak et al. (2010) used only visual interpretation for sites of minor change and Corel Draw

Table 1
Comparison of landslide area and vegetation cover in repeat photographs from 2005, 2007, and 2010 (in percent of all revisited locations).

Inventories	No or minor change in landslide area	Vegetation recovery	Increase in landslide area	Reference
2005 vs. 2007	80	11	9	Khattak et al. (2010)
2005 vs. 2007	59	32	9	This study
2007 vs. 2010	56	31	13	This study
2005 vs. 2010	46	44	11	This study

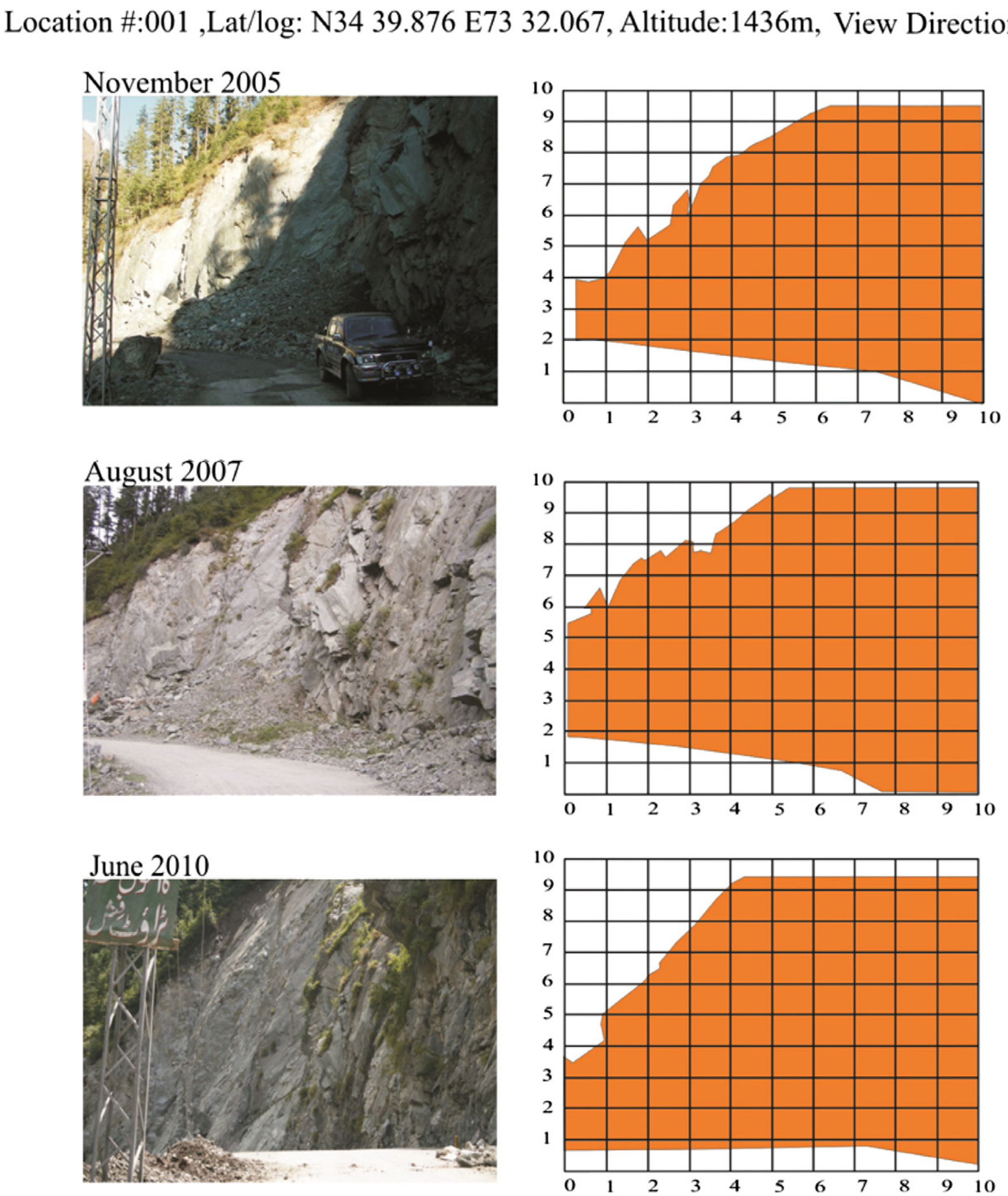

Fig. 5. Example of repeated photography using location #001 from 2005, 2007, and 2010 (left) and landslide area (in orange on the right). The landslide area remained almost unchanged over the five years (2005 photograph from inventory by Owen et al., 2008; 2007 photograph from inventory by Khattak et al., 2010; 2010 photograph this study).

whenever vegetation growth was at least 5%. In our study, we used AutoCAD and Corel Draw for all sites.

Our study revealed that from 2007 to 2010 the number of sites with new or reactivated landsliding increased by 4%; at the same time, the number of sites with vegetation growth remained the same. From 2008 to 2010 annual precipitation was close to the mean values; the slight increase in landslide activity was insignificant and within the range of normal yearly fluctuations. We support the view of Khattak et al. (2010) and Saba et al. (2010) that the landscape stabilized within only two or three years after the 2005 earthquake.

The impact of precipitation, particularly during the monsoon months, on slope stability and post-seismic landslide activity in the study region is still unclear. Khattak et al. (2010) analyzed the change in landsliding between November 2005 and June/August 2007—a period that included the relatively wet year 2006—by repeating 68 of the original 164 locations in Owen et al.'s (2008) inventory and found that 80% of the sites showed no change, 11% showed vegetation growth on the landslide scars and masses, and only 9% showed an increase in landslide area (Table 1). Our study presents the same number (9%) for sites with an increase in landslide area. Khattak

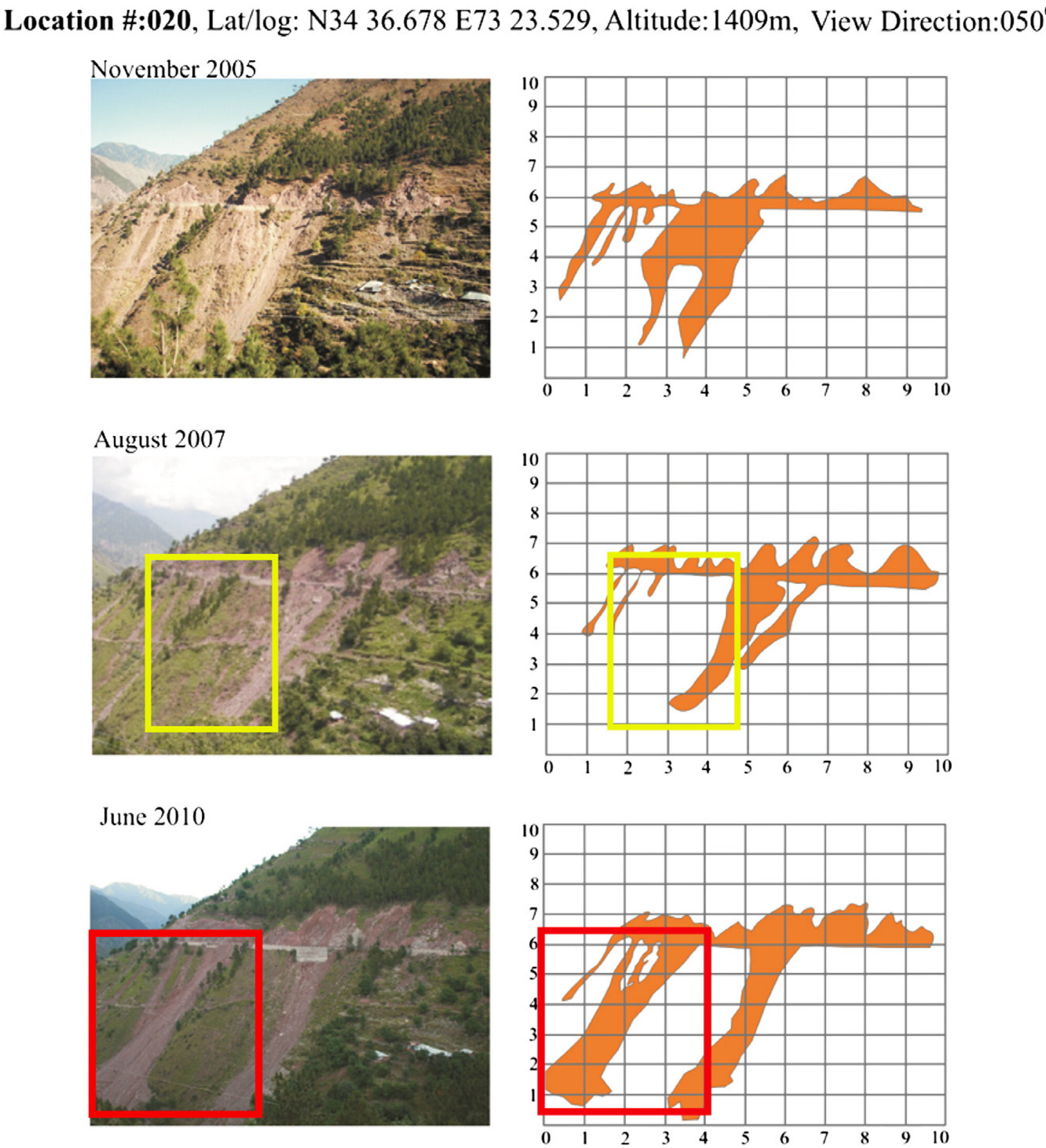

Fig. 6. Example of repeated photographs using location #020 from 2005, 2007, and 2010 (left) and landslide area (in orange on the right). Although in some smaller parts the vegetation regrew (yellow box), landsliding continued (red box) (2005 photograph from inventory by Owen et al., 2008; 2007 photograph from inventory by Khattak et al., 2010; 2010 photograph this study).

et al. (2010) concluded that for triggering landslides a specific threshold of soil pore water pressure must be attained because pre-earthquake conditions were relatively dry. This threshold had not been reached in 2005 and, therefore, the co-seismic landsliding was lower than was expected for an earthquake of such a high magnitude. Khattak et al. (2010) further concluded that, in general, rainfall did not play a major role in activating landslides in their large study area (2550 km^2); thus, despite the heavy rains in 2006, the co-/post-monsoon landsliding was less extensive than had been predicted.

In contrast, for their much smaller study area (36 km^2) around Muzaffarabad, Saba et al. (2010) showed that the number of landslides increased by 35% from 117 in 2004 to 158 in 2005 and thereafter by 147% to 391 landslides in 2006. Despite the fact that 2008 (1713 mm) was wetter than 2007 (1213 mm), the number of landslides increased only by 2 in 2007 and by 1 in 2008; and the increase in landslide area was almost identical and almost negligible (0.06 and 0.08 km^2). Saba et al. (2010) explained that the very high number of additional failures, particularly rock falls during the wet summer of 2006 was caused by rain seepage into co-seismic fissures and that after 2006 the landscape had stabilized. Saba et al. (2010) hypothesized that in 2007 and 2008 either the rainfall intensity did not reach the threshold for causing rock falls or the 2005 earthquake and its aftershocks had already caused

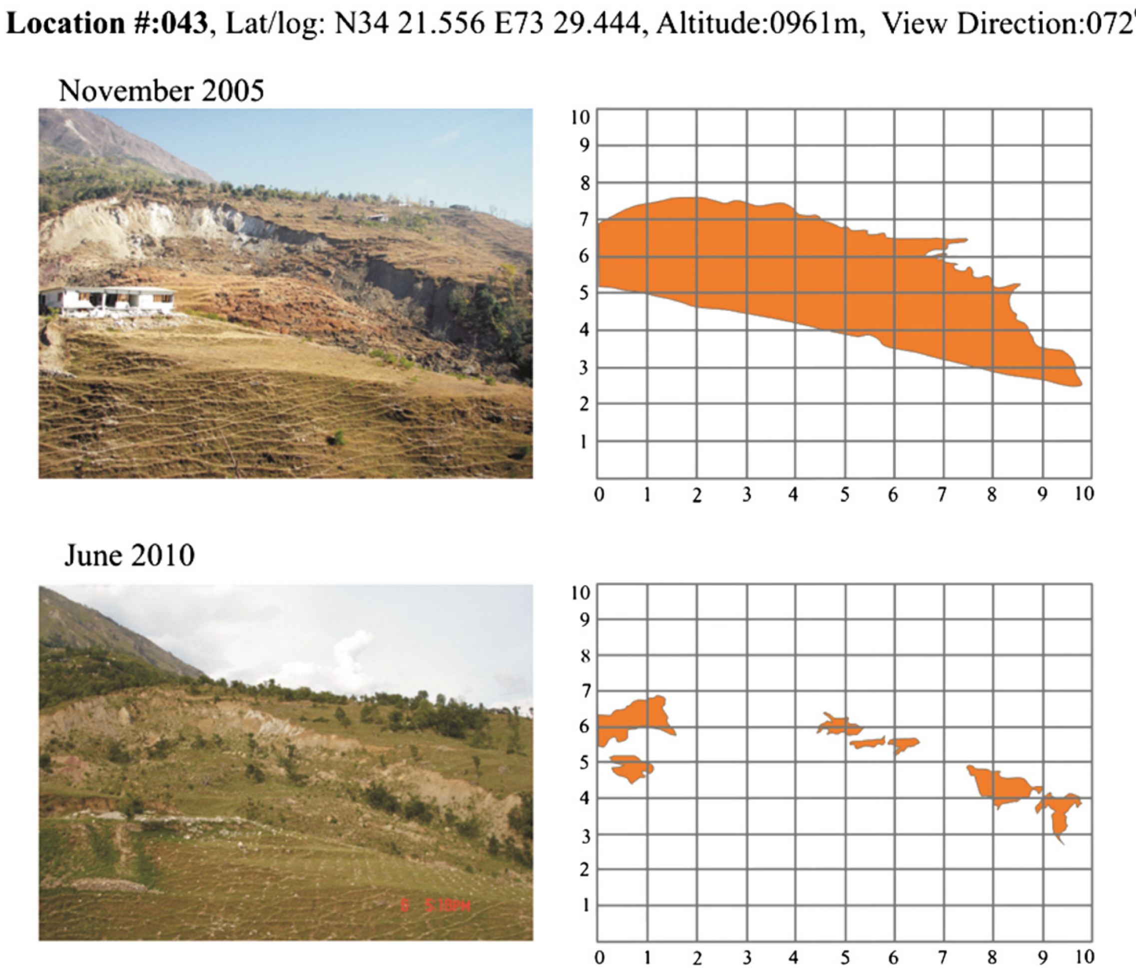

Fig. 7. Example of repeated photographs using location #043 from 2005 to 2010 (left) and landslide area (in orange on the right). By 2010, landsliding became almost inactive and vegetation regrew (2005 photograph from inventory by Owen et al., 2008; 2010 photograph this study).

all unstable rocks to fall. A positive correlation between higher rainfall and increased landslide intensity was also postulated by Sudmeier-Rieux et al. (2007b) who argued that heavy rains in March 2007 triggered a number of landslides on slopes with active landsliding and fissures in their relatively small study area (~100 km^2) in the lower Neelum valley to the NE of Muzaffarabad.

We argue that the contradictory conclusions about the impact of above-normal rainfall on post-seismic slope stability in the study region as presented in Khattak et al. (2010) and our study on the one side and in Sudmeier-Rieux et al. (2007b) and Saba et al. (2010) on the other side relate to the size of the three study areas. While Sudmeier-Rieux et al. (2007b) and Saba et al. (2010) presented case studies focused on relatively small sites in the nearer surroundings of Muzaffarabad, Khattak et al. (2010) and our study are at a regional scale. Although Khattak et al. (2010) and our study showed an increase in landslide activity triggered by rainfall between 2005 and 2007 at several locations, particularly around Balakot and in the Neelum valley, this is not the case for the wider earthquake-affected region. In contrast, the vast majority of revisited locations showed no change in landslide activity between 2005 and 2007 despite the heavy monsoon rains in 2006.

In contrast to the uncertainties in assessing the role of precipitation on slope stability, it has been documented that vegetation helps in stabilizing slopes in the study region (Kamp et al., 2010; Peduzzi, 2010). For Peduzzi's (2010) 3600-km^2 study area, the vegetated slopes had less and smaller landslides: while forests cover 45% of the area, only 17% of landslides occurred there; deforested and grazing land covers 42% of the area, and 55% of the landslides were triggered there. Peduzzi (2010) concluded that vegetation plays a significant role in stabilizing slopes. Similar results were presented by Kamp et al. (2010) who showed in their 2250-km^2 study area that forest cover greatly reduces landsliding: with only 2.3% of the total landslide area within forests, which cover 45% of the total study area; in contrast, 67% of the landslide area was under shrubs/grassland vegetation, which covers 42% of the total study area. However, as important as vegetation may be in slope stabilization, Popescu (2002) mentioned that it may also destabilize slopes to some extent by adding weight and acting as a surcharge.

While clearly vegetation probably helped protect slopes from landsliding during the earthquake, we cannot quantify its role for slope stabilization in post-seismic years. We favor the view of Khattak et al. (2010) who concluded that—although individual landslides might have been triggered by rainwater infiltrating fissures—many of the slopes stabilized indirectly from rainwater in the long run because it hastened recovery of the vegetation and, consequently, increased its pore-water capacity and transpiration, which reduces soil moisture. However, landslide stabilization is usually the result of root structures, which in the study area probably do not develop quickly enough to be much influenced by one or two seasons, and the majority of failures were rock falls associated with bare slopes.

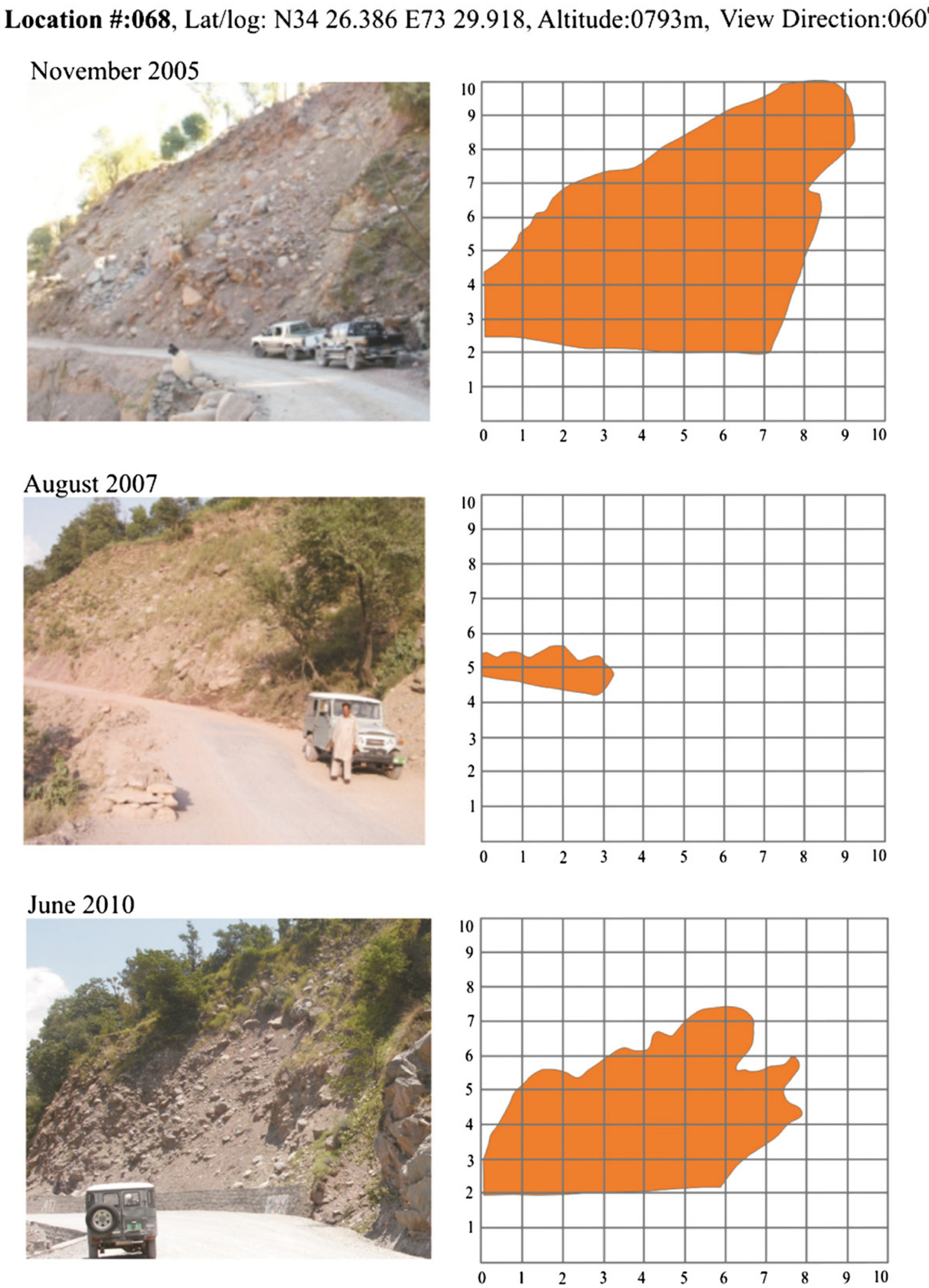

Fig. 8. Example of repeated photographs using location #068 from 2005, 2007, and 2010 (left) and landslide area (in orange to the right). Although at this road cut vegetation first successfully re-grew and stabilized the slope between 2005 and 2007, new landsliding occurred thereafter by 2010 (2005 photograph from inventory by Owen et al., 2008; 2007 photograph from inventory by Khattak et al., 2010; 2010 photograph this study).

Furthermore, most landslides were shallow failures; in which case, vegetation can more effectively aid in slope stability.

For landslides triggered by the 1999 Chi-Chi earthquake in central Taiwan, Chou et al. (2009) detected a general vegetation recovery rate of 86% within six years; the recovery rate declined along landforms from ridgeline to stream banks. For the Chiufenershan landslide triggered also by the Chi-Chi earthquake, Lin et al. (2008) concluded that natural succession will restore the original vegetation in a few years.

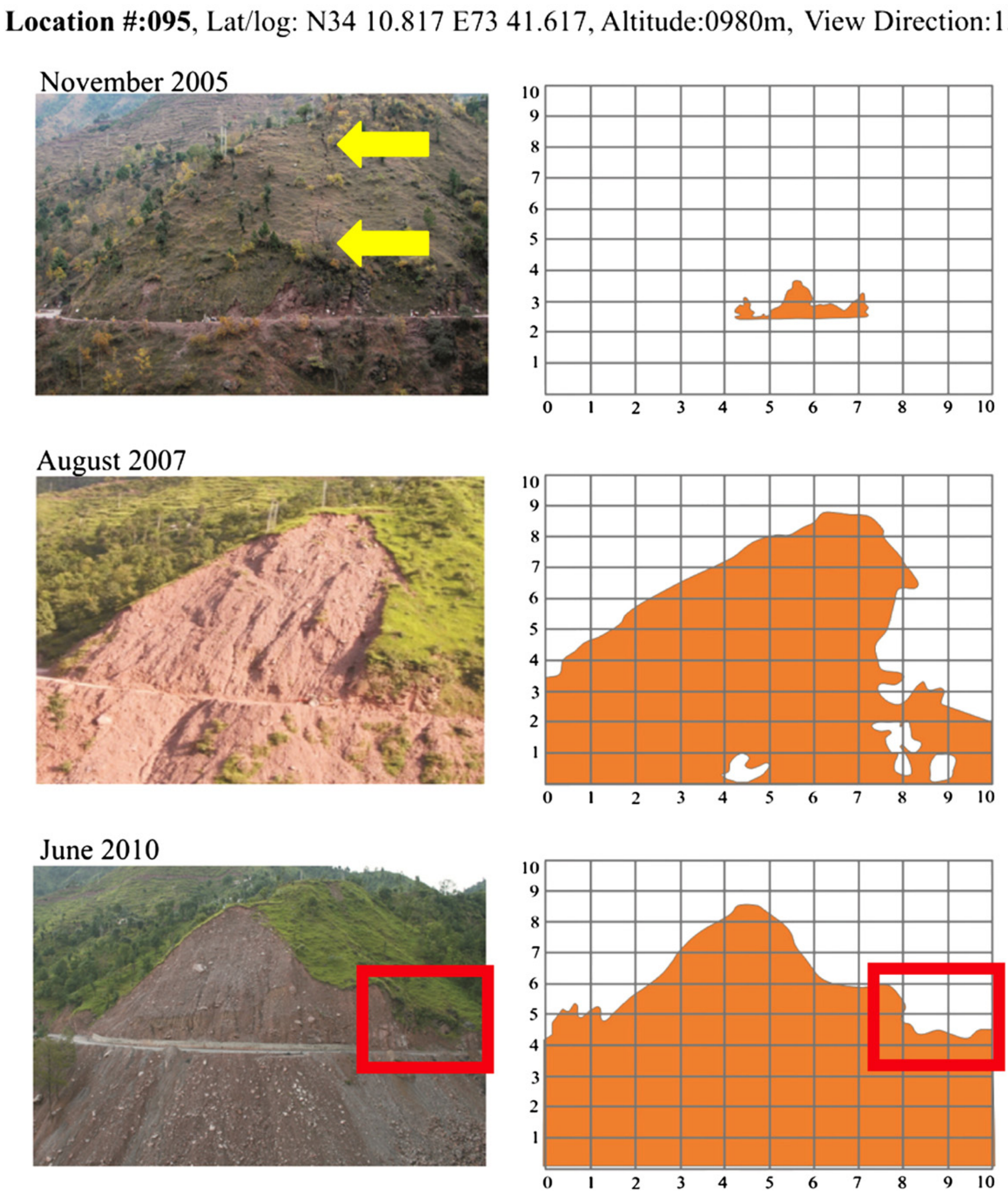

Fig. 9. Example of repeated photographs using location #095 from 2005, 2007, and 2010 (left) and landslide area (in orange to the right). At this road cut, from 2005 to 2007 fissures (yellow arrows) developed into extensive landsliding; thereafter, the landslide area increased only slightly by 2010 (red box) (2005 photograph from inventory by Owen et al., 2008; 2007 photographs from inventory by Khattak et al., 2010; 2010 photograph this study).

Nevertheless, our field observations in the 2005 Kashmir earthquake region revealed that sites at lower elevations recovered faster than those at higher elevations, which presumably is caused by enhanced vegetation growth and little or no snow accumulation during the winter months at lower elevations. However, in our study we were not able to quantify the impact of vegetation on slope stabilization.

Our study supports the view of others (Sudmeier-Rieux et al., 2007a; Kamp et al., 2008, 2010; Owen et al., 2008; Khattak et al., 2010) that much of the co- and post-seismic landsliding was related to river erosion, road construction, agricultural practices and activities, and building construction. After all, 44 (35%) of the 123 revisited landslide sites in 2010 documented new or reconstruction of roads and buildings, and many of these sites showed reactivated or increased landsliding.

Much of the existing literature predicted an increased post-disaster landslide hazard related to extensive fissuring and human impact; however, none of these studies quantified the risk (Sudmeier-Rieux et al., 2007a,b; Kamp et al., 2008, 2010; Owen et al., 2008; Khattak et al., 2010). We support the view that throughout the study region landsliding is a continuous and pervasive hazard in general that requires risk assessment and management.

7. Conclusion

After the 8 October 2005 Kashmir earthquake, numerous studies predicted that the earthquake-affected region faces a potential hazard from above-normal post-seismic landsliding for many years to come (Sudmeier-Rieux et al., 2007a,b; Kamp et al., 2008, 2010; Owen et al., 2008; Khattak et al., 2010). Our study, however, shows that in 2010, five years after the seismic event, no sign of such specifically earthquake-related landslide hazard exists. The comparison of repeated photography from 2005, 2006, 2007, and 2010 revealed that the majority of revisited landslide sites showed no change in landslide activity and that many showed a significant vegetation regrowth. After only two to three years, the landscape has apparently stabilized. However, ongoing landsliding is dominantly the consequence of human activity including (re)construction and agriculture. The increased monsoon rainfall in 2006 did not trigger significantly more landsliding throughout the wider earthquake-affected region, although it did in several spatially limited locations. While an assessment of the vegetation regrowth rate and of the impact of vegetation regrowth on slope stabilization in the study area remains difficult, a positive relationship between vegetation regrowth and slope stability seems to exist; on many slopes vegetation did indeed regrow. In the study region, landsliding is a substantial surface process frequently shaping the landscape; it is, thus, a pervasive hazard that needs our attention.

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Appendix A. Supplementary data

Online supplementary data (repeated photographs) can be found at: ftp://ftp.spatial.umt.edu/kashmir.

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