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The supplementary material (Tables S6–S9, Figures S1–S7) follows the references in this file. The data, code and spreadsheet tables S1–S5 are available from the author on request (smeena@ogs.it) and will be published on Zenodo with a persistent identifier.

Mapping landslide change and volume with repeat airborne LiDAR after the May 2023 Emilia-Romagna event: slope-dependent detection limits and lowered areas

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Abstract

Landslide inventories are validated against repeat topography by comparing the ground that changes beyond a detection limit inside mapped polygons with the same fraction on stable ground. Stable ground is gentler than landslides, and LiDAR noise grows with slope. We measure the consequence for the May 2023 Emilia-Romagna event, Italy, with four pairs of 0.5 m airborne LiDAR on 919 river-corridor tiles, the only ground where pre- and post-event surveys overlap, and the 80,997-polygon RER2023 inventory. Stable ground exceeds a tile's 95th-percentile limit on 4% of flat ground and 27% of slopes above 40°, so the rate that applies to the landslides is 13.7%, not 5.9%, and the usual comparison doubles the apparent signal. A fifth pair spanning the first post-event year is consistent with the slope-matched floor in aggregate (14.5% against 14.2%, where all stable ground predicts 6.1%), although gentle and steep ground depart from it in opposite directions. With the corrected floor, 36% of mapped landslide ground changed by more than about 0.5 m. Only 20% of the mapped area of debris and earth landslides was lowered beyond the limit, mostly in the upper half of each polygon, and the same estimator finds no lowering in the post-event year. Area–volume scaling applied to the outlines overstates the measured lowering 8 to 11 times, and on the lowered area the exponent is about 1.1 to 1.3 rather than 1.45. Inventory validation needs slope-matched floors, and inventory-based volumes need lowered or source areas.

Keywords. airborne LiDAR; DEM of difference; detection limit; landslide inventory; landslide volume; area–volume scaling; Emilia-Romagna

1. Introduction

Inventories compiled after a regional rainfall or earthquake event record where landslides were seen, not how much ground moved (Malamud et al., 2004; Guzzetti et al., 2012). Volumes, depths and the difference between a fresh failure and a reactivated scar need the third dimension, and for a whole event that dimension comes only from repeat topography (Jaboyedoff et al., 2012; Tarolli, 2014; Passalacqua et al., 2015). Event-wide differencing is now established: DeLong et al. (2022) differenced 8,000 km² of repeat lidar after a Minnesota storm, Bernard et al. (2021) built three-dimensional inventories from repeat point clouds, Yunus et al. (2023) and Kudo et al. (2026) measured the depths of thousands of soil landslides in Japan, and Massey et al. (2020) and Jones et al. (2025) measured the source volumes of the Kaikōura landslides from a 6,875 km² difference model. Earlier work differenced single slopes or catchments (Corsini et al.,

2009; Bull et al., 2010; Ventura et al., 2011; DeLong et al., 2012; Mora et al., 2018), Ardizzone et al. (2007) used post-storm lidar to revise an inventory, and Scheip et al. (2026) argued from post-Helene lidar that both pre-event and rapid post-event surveys are needed. In Italy the stock of regional surveys is growing, but it is flown for cartography rather than monitoring (Casagli et al., 2023).

Two uses of repeat topography with an inventory recur. The first is validation: the ground beyond a detection limit inside the mapped polygons is compared with the same fraction on stable ground, the limit being calibrated on stable ground (Brasington et al., 2000; Lane et al., 2003; Wheaton et al., 2010; Lague et al., 2013). That limits vary with slope and other covariates is known (Wheaton et al., 2010; Hugonnet et al., 2022). What the variation does to the inside–outside comparison has not, to our knowledge, been quantified: stable ground in a landslide region is mostly gentle and mapped landslides are mostly steep, so a limit that is right on average is exceeded by noise more often inside the polygons than outside them. Nor has a corrected floor been tested where little change is expected on the same polygons. The second use is volume. Event volumes are usually obtained by applying an area–volume relation to inventory polygons (Guzzetti et al., 2009; Larsen et al., 2010), although at Kaikōura the relation had to be fitted to source areas, separated from runout, to give the measured volumes (Massey et al., 2020). Rainfall inventories rarely separate source from runout, and how much of their mapped area actually lost material has seldom been measured.

The May 2023 Emilia-Romagna event offers both tests. Two rainfall pulses triggered the 80,997 landslides of the RER2023 inventory (Berti et al., 2025), the region has flown three generations of 0.5 m airborne LiDAR since 2022, and emergency LiDAR was flown along the river corridors within weeks of the event and again the following spring. A Copernicus emergency activation estimated volumes on 23 small areas from UAV photogrammetry (EMSN156, 2023), and imagery has yielded further inventories and detectors (Ferrario and Livio, 2024; Dal Seno et al., 2026; Berti et al., 2026), but no study has differenced LiDAR for the event. Okyay et al. (2019) note that pre- and post-event airborne lidar “is still uncommon”; the region holds every way it can arise, by planned overlap, by re-flights recorded in a flight log and by a disaster forcing a new survey.

We make four contributions. First, we quantify the slope bias of a tile-wide detection limit on 1,514 tile-pairs and correct it with a slope-matched noise floor and a slope-binned limit (Sections 3.2 and 4.3). Second, we test the correction on a pair spanning the first post-event year, class by slope class, and use the three surfaces of each tile to separate the error of each survey (Sections 3.3 and 4.4). Third, we measure the area lowered beyond the limit in every scored polygon, with the post-event year as a negative control, and test area–volume scaling on it and on the mapped outline (Sections 3.4 and 4.6). Fourth, an audit of the regional LiDAR stock shows why the river corridors are all there is, and a comparison with EMSN156 checks the volumes against the only prior estimate (Sections 4.1 and 4.7).

2. Study area and data

2.1 The May 2023 event and the RER2023 inventory

The Romagna Apennines between the Santerno and the Savio rivers (Fig. 1) are built mainly of the Miocene Marnoso-Arenacea Formation, a turbidite flysch of sandstones and pelites, with Pliocene clays

and their badlands along the foothills; the clay shales, marls and chaotic complexes that host the dormant earthflows of the northern Apennines lie mostly outside this belt, to the west in Emilia (Berti et al., 2025) and in the east of the region. Two rainfall pulses hit it in May 2023: about 200 mm in 48 h on 1–3 May, then 200–250 mm in 48 h on 16–17 May, each with a return period of 100–300 years and together exceeding 500 years (Berti et al., 2025).

The RER2023 inventory, version 1 (Berti et al., 2025; Pizziolo et al., 2024; CC BY 4.0), holds 80,997 polygons covering 8,383 ha, with a median polygon of 479 m². It was digitised at 1:200 to 1:800 on 0.2 m aerial photography of 23 May 2023, compared with 2020 imagery, checked against the 1:10,000 regional topographic map and viewed in three dimensions on the 30 m Copernicus GLO-30 DEM; no LiDAR surface was used, so it is independent of the differencing reported here. Each polygon encloses source and runout together. The harmonised field ClassNew separates debris slides (DS1, DS2), debris flows (DF1, DF2), earth slides (ES), earth flows (EF) and rock slides (RS1, RS2): material follows the lithological unit at the polygon centroid, slide and flow are separated by a convolutional network that reads the polygon shape (F1 score 0.80), and the subtypes by thresholds on a green-leaf index (0.08; DS1, DS2) and on the share of the landslide area on unforested slopes (0.3; DF1, DF2); rock-block slides were classified by hand. In the clay units most earth slides and flows are reactivations, whereas almost all failures in the coarse-grained units, which make up most of the Romagna belt, were first-time failures on slopes without documented landslides. The authors put missed and false landslides at under 1% and name boundary precision as the main limitation; outlines of fluidised slides join debris patches across vegetation. Version 1 is the only published version as of October 2026.

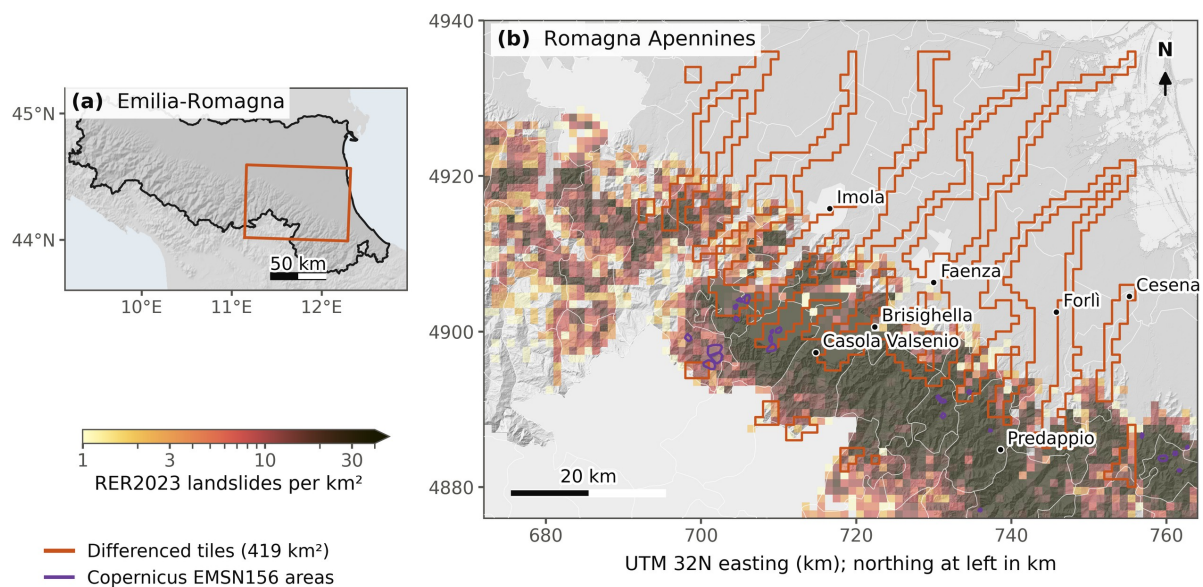


Figure 1. Study area. (a) Emilia-Romagna on shaded relief; the box is panel (b). (b) The Romagna Apennines on shaded relief from the 25 m regional DTM: density of RER2023 inventory polygons (landslides per km², 1 km cells), 1 km tiles with at least one differenced pair (outlined), and the Copernicus EMSN156 areas of interest (purple).

2.2 The LiDAR stock and the survey pairs

We compiled every airborne LiDAR survey known to cover any part of Emilia-Romagna (22,501 km²): 39 surveys from 2004 to 2025, with flight windows, densities, accuracies, access routes and an evidence

link per fact (Table S6, Section 7). All differenced surfaces are 0.5 m bare-earth grids in RDN2008/UTM 32 (EPSG:7791), served by Web Coverage Service under CC BY 4.0. The three regional generations are RER 2022 (1,434 km², 9 February 2022 – 14 January 2023), RER 2023–24 (11,278 km², 23 March 2023 – 13 January 2025) and RER 2025–26 (1,441 km² so far); the post-event surfaces are the CGR emergency corridors, flown along 23 river systems between 2 June and 18 July 2023, and the APC Fiumi 2024 corridors, flown between 13 March and 17 June 2024. For display, the AGEA 2020 orthophoto and the CGR emergency orthophoto of May 2023 (0.2 m), on which RER2023 was mapped, are read from the regional Web Map Service.

Five pairs are differenced (Table 1). RER 2023–24 tiles whose flight dates all fall before 2 May 2023 form a pre-event surface flown three days to six weeks before the first pulse (Fig. S1); the RER 2022 block over the Vena del Gesso, Imola and Faenza was flown on 23 March 2022 and is also the pre-event surface of EMSN156. Pairs C and A2 end in the 2023 emergency surface and form the event window; pairs B and A end in the 2024 surface and form the long window, the main sample. Pair D differences the two post-event surfaces and spans the first post-event year.

Table 1. The five survey pairs.

Pair	Pre-event surface	Post-event surface	Interval	Role	Tiles	Area analysed (km ²)
C	RER 2023–24, flown 23 Mar – 28 Apr 2023	CGR emergency corridors, 2 Jun – 18 Jul 2023	1–4 months	Event window	622	242.9
B	RER 2023–24, flown 23 Mar – 28 Apr 2023	APC Fiumi 2024, 13 Mar – 17 Jun 2024	10–15 months	Long window	663	297.0
A2	RER 2022, 23 Mar 2022	CGR emergency corridors, 2 Jun – 18 Jul 2023	14–16 months	Event window, month of EMSN156	95	33.0
A	RER 2022, 23 Mar 2022	APC Fiumi 2024, 13 Mar – 17 Jun 2024	24–27 months	Long window	134	61.9
D	CGR emergency corridors, 2 Jun – 18 Jul 2023	APC Fiumi 2024, 13 Mar – 17 Jun 2024	8–12 months	Post-event year, null test	579	218.6

The interval is from pre-event flight to post-event flight. Tiles are 1 km grid cells with valid data on both surfaces after processing; the area is the valid overlap.

3. Methods

3.1 Differencing and co-registration

Pairs are differenced on the regional 1 km grid, each cell fetched whole as a 2,000 × 2,000 pixel GeoTIFF per surface; cells are addressed by grid coordinates because the tile indices omit ground the rasters cover and APC Fiumi 2024 mixes two naming schemes. Slope comes from the pre-event surface, and a

height-above-nearest-drainage proxy (pre-event elevation minus the minimum in a 250 m window) marks floodplain below 3 m. Horizontal co-registration follows Nuth and Kääb (2011), generalising Berthier et al. (2006), on stable pixels with slope between 5° and 40° ; a shift is accepted only if it at least halves the residual, does not worsen the stable-ground NMAD by more than 5%, is at most 1.0 m and is estimated on at least 1 ha of calibration ground, and every statistic was also computed without it. The median stable-ground difference is removed as a vertical offset. The 2023 emergency surface contains planar facets where a triangulated surface spans gaps in the ground points (Fig. S2); in either surface we mask connected areas of at least 500 m^2 in which a plane fitted to every 7×7 pixel window leaves a residual below 0.7 cm and whose median absolute difference from the other surface exceeds 1 m. One script per tile writes a JSON record, the difference raster and a bit mask; 1,514 tile-pairs on 919 distinct tiles were usable for pairs A, B, C and A2, and pair D was run from the cached surfaces.

3.2 Detection limits and the noise floor

The calibration class on each tile is valid ground more than 30 m from any mapped landslide, outside the floodplain, with slope at most 35° and $|\text{dh}|$ below 3 m; the 95th percentile of $|\text{dh}|$ on it is the tile detection limit, empirical because the error distributions of operational LiDAR pairs have heavy tails (Höhle and Höhle, 2009; Anderson, 2019). The broad stable class is the same ground without the slope and $|\text{dh}|$ cuts. The limit is tested on held-out halves of a 100 m checkerboard, with the landslide buffer widened to 60 and 100 m, and without co-registration; spatial correlation is measured as the semivariogram of the calibration-class difference, and random volume uncertainty follows Rolstad et al. (2009) and Hugonnet et al. (2022).

Let p_{ls} be the fraction of mapped-landslide ground beyond the limit and p_{st} the same fraction on the broad stable class. The enrichment is $p_{\text{ls}} / p_{\text{st}}$ and the changed fraction $(p_{\text{ls}} - p_{\text{st}}) / (1 - p_{\text{st}})$, which treats landslide ground as a mixture of changed ground, all of it detected, and unchanged ground exceeding the limit at the stable rate. Because the limit is a 95th percentile, p_{st} is near 5% by construction, and both summaries assume that the noise inside the polygons is that of stable ground, which fails when the two have different slopes. We correct this two ways. The slope-matched floor keeps the tile limit and replaces p_{st} by $\sum_k w_k p_{\text{st},k}$, the stable-ground exceedance in nine slope classes weighted by the landslide area in each; it is our estimate. The slope-binned limit tests each pixel against the 95th percentile of its own slope class, a one-covariate version of the spatially variable limits of Wheaton et al. (2010) and Hugonnet et al. (2022); it brings p_{st} to about 5% in every class but discards real change between the tile limit and the class limit, and gives a conservative bound. Volumes are treated alike: the thresholded volume per hectare of stable ground in each slope class is the background, from noise and from real change on unmapped ground, and subtracting it class by class gives background-corrected volumes.

3.3 The post-event null test and the three-surface decomposition

On 570 of the 579 pair-D tiles the pre-event surface also exists (124 of them hold mapped landslides), so the long-window difference L is the sum of the event-window difference E and the post-event difference D . If the landslides changed little between the 2023 and 2024 flights, pair D is a null test of the floor: on the same steep polygons the right floor should predict the exceedance and the wrong one should report a signal.

Strictly, the test shows whether landslide ground changed more than unmapped ground of the same slope, so it measures the slope bias of the all-stable reference rather than proving the landslides inert. We read it in aggregate and class by class, with a tile bootstrap, and in a strong form in which the floor is recalibrated on pair D, either by scaling each stable class by its pair-D ratio of landslide to stable exceedance or by using the pair-D landslide rate itself. If the three surfaces carry independent errors of variance s_{pre} , s_{23} and s_{24} , the stable-ground variances $var(E) = s_{pre} + s_{23}$, $var(D) = s_{23} + s_{24}$ and $var(L) = s_{pre} + s_{24}$ can be solved for the error of each survey; we use NMAD² on ground stable in all three differences. The solution is conditional on independence, which the data cannot test, because $L = E + D$ makes $cov(E, D) = -s_{23}$ an identity.

3.4 Scoring, volumes and source areas

A polygon is scored if at least half of its area has valid data on both surfaces; a polygon cut by tile edges is pooled across tiles and scored once. For each we record its detected fraction under both limits, its slope distribution, the detected fraction in a 2.5 m rim and in its core, and lowered and raised volumes over the pixels beyond the tile limit, with per-pixel changes capped at 8 m. Scored and unscored polygons are kept so that the sample can be compared with the inventory (Table S7); as a check, pair A was also scored on the Region’s administrative inventory (“Frane maggio 2023”, 63,684 polygons; Regione Emilia-Romagna, 2024), with corridor-wide statistics identical to the first decimal.

The area lowered beyond a threshold is measured, not mapped. Per polygon and slope class k , n_{low} of n valid pixels are lowered beyond the threshold; with p_k the share of stable ground of the same tile and class that noise lowers beyond it and v_k the lowered volume per stable pixel, the lowered area is $x = \sum_k (n_{low,k} - p_k n_k) / (1 - p_k)$ pixels and the lowered volume $V = V_{low} - \sum_k v_k (n_k - x_k)$, so that noise is removed alike from area and volume; sums are not clipped at zero. Three noise models bracket the correction: none, stable ground as above, and stable ground rescaled class by class by the ratio of landslide to stable lowering in the post-event year. Five thresholds are used, the tile limit and 0.2, 0.3, 0.5 and 1.0 m. The lowered area is not a source area in the sense of Massey et al. (2020), who digitised sources separately: it misses thinning below the threshold and includes channel incision, bank retreat and any lowering of runout, so it is always reported with its threshold. Rock slides, whose lowering is largely displacement, are analysed separately. The relation of Guzzetti et al. (2009), $V = 0.074 A^{1.450}$ with A in m^2 and V in m^3 , fitted to whole-landslide areas and volumes of all types, is applied to the mapped and to the lowered area of each scored polygon, all pro-rated from the valid to the full polygon. The exponent of lowered volume on lowered area is estimated as one plus the least-squares slope of log mean lowering on log lowered area, which keeps area off both sides of the regression, and by reduced major axis, for polygons with at least 25 m^2 lowered (10 to 500 m^2 as a sensitivity test), with 95% intervals from 300 bootstrap resamples of tiles. A simulation maps true to observed exponents: sources of 25 to 6,000 m^2 with paraboloid depth are embedded in polygons five times larger, with pixel noise drawn from stable-ground differences of 30 pair-B tiles and the same threshold, correction and fit. The post-event year, pair D, is run through the same estimator as a negative control. For scale only, Section 5.2 multiplies the mean corridor lowering by the inventory area; a stratified ratio estimator (class $\times$ 25 m slope $\times$ size, at least 15 polygons per stratum) serves as a sensitivity check of that product.

3.5 Overlap audit and comparison with EMSN156

Every tile polygon of the audited surveys was taken from the regional tile-index service and dissolved per survey; overlaps are exact polygon intersections in EPSG:25832. Every RER 2023–24 tile was classified from its flight dates, and for tiles with passes on both sides of the event we read the WCS DescribeCoverage response and the mosaic catalogue to see whether individual passes are served. The Copernicus EMSN156 activation (IABG and GMV, report of 11 July 2023) delineated 360 landslides on 23 areas of interest on 5 cm UAV imagery flown 31 May – 5 June 2023 and estimated volumes as the plain difference between the RER 2022 surface and a UAV photogrammetric surface, with a per-area vertical shift and no detection limit; the report calls them “a rough estimation only”. We compare every EMSN156 polygon with at least half of its area covered by a pair, summing both estimates over the pixels valid in the pair.

4. Results

4.1 Repeat coverage is almost entirely disaster-driven

The three regional generations overlap on under 1% of their area and on no ground all together (Fig. 2, Table S8). RER 2022 and RER 2023–24 share 30.3 km², 24.0 km² of it in Valmarecchia; Comune di Modena 2024 overlaps RER 2023–24 on 109.6 km², two months apart. The flight log records 204 RER 2023–24 tiles (191.8 km²) with a pass before 2 May 2023 and another on or after 17 May, but they are not retrievable: the coverage has no time axis, and the mosaic catalogue holds one source raster per tile with the mosaic operator set to “first”. The pairs that bracket the event were created by the emergency surveys: the 2023 corridors meet the pre-event RER 2023–24 tiles on 249 km² and the 2024 corridors on 311 km², and the RER 2022 block meets them on 34 and 69 km².

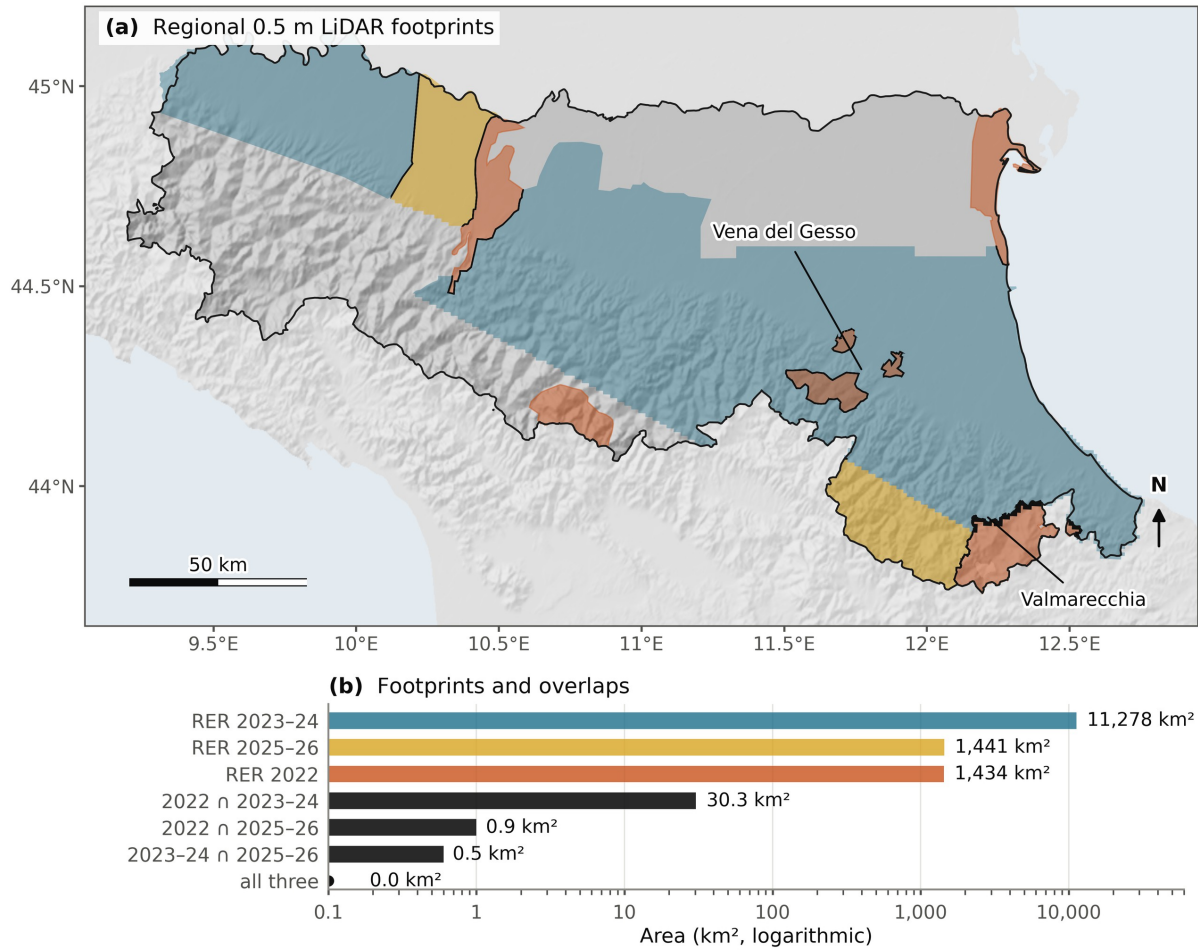


Figure 2. (a) Footprints of the three regional 0.5 m LiDAR generations on shaded relief (RER 2022, orange; RER 2023–24, teal; RER 2025–26, gold); their overlaps are drawn in black. (b) Area of each survey and of each overlap, on a logarithmic scale. Overlaps are exact polygon intersections of the live tile indices (11 October 2026).

4.2 Error budget

Table 2. Noise on stable ground and detection limits: median over tiles (interquartile range), except the last two columns, which are pooled over tiles.

Pair	Tiles	NMAD (cm)	Detection limit (cm)	Limit / (1.96 NMAD)	99th percentile dh (cm)	Stable ground beyond limit	Stable ground beyond 1 m
A RER 2022 → 2024	134	8.3 (5.9–10.3)	42 (34–54)	2.6	100	6.4%	2.0%
B RER 2023–24 → 2024	663	9.4 (6.9–14.4)	46 (34–61)	2.3	90	5.7%	1.5%
A2 RER 2022 → 2023	95	8.2 (5.9–10.1)	61 (42–83)	3.7	159	7.7%	5.4%
C RER 2023–24 → 2023	622	10.3 (7.1–13.8)	49 (36–71)	2.4	109	6.4%	3.3%
D CGR 2023 → APC 2024	579	10.4 (7.2–17.2)	58 (45–78)	2.7	119	6.5%	3.5%

NMAD, normalised median absolute deviation of the stable-ground difference after co-registration; the detection limit is the empirical 95th percentile of |dh| on the calibration class (Section 3.2); the ratio is the median over tiles of the per-tile limit divided by 1.96 NMAD; the last two columns use the broad stable class.

The surveys meet their 8 cm specification in the core of the error distribution, but the 95th percentile of $|dh|$ is 2.3 to 3.7 times the Gaussian value (Table 2, Fig. S3): 45 cm in the 797 long-window tile-pairs (interquartile range 34–60 cm). The limit is stable under resampling (held-out exceedance 5.11% of the calibration class against a nominal 5.00%); widening the landslide buffer to 100 m lowers it from 44 to 40 cm on the 218 tiles with landslide ground and raises the landslide exceedance from 44.7% to 50.4%, so the default is conservative; removing co-registration changes the long-window exceedances by under 0.1 points. The stable-ground difference is correlated to at least 145 m in the long window and 208 m in the event window. The 2023 emergency surface is the weak point: the facet mask removes 0.95% of its overlap on average, but the 103 tiles where it removes more than 1% hold 34% of the event-window landslide area. On ground stable in all three differences of the 477 RER 2023–24 triplets, the decomposition gives robust standard deviations of 7.3, 6.5 and 8.3 cm for the pre-event, 2023 and 2024 surfaces (5.9, 6.3 and 5.0 cm on the 86 RER 2022 triplets), assuming independent errors, which gives a negative variance for at least one surface on 9%–13% of the RER 2023–24 triplets and 2%–5% of the RER 2022 ones (the medians include them): the emergency surface is no noisier in the core, and its problems are in the tails.

4.3 A tile-wide limit doubles the apparent signal

Table 3. Detection against the RER2023 inventory by pair and by group: with the tile limit against all stable ground, against slope-matched stable ground, and with the slope-binned limit.

Pair or group	Tile-pairs	Landslide ground beyond tile limit	Stable ground beyond tile limit	Enrichment	Slope-matched stable rate	Enrichment, slope-matched	Changed fraction, slope-matched	Changed fraction, slope-binned limit
A	134	45.2%	6.4%	7.1	–	–	–	–
B	663	44.2%	5.7%	7.7	–	–	–	–
Long window (A + B)	797	44.7%	5.9%	7.6 (7.2–8.0)	13.7%	3.3 (3.0–3.5)	36% (33%–38%)	25% (22%–27%)
C	622	32.6%	6.4%	5.1	–	–	–	–
A2	95	40.8%	7.7%	5.3	–	–	–	–
Event window (C + A2)	717	36.6%	6.6%	5.5 (5.0–6.1)	17.0%	2.2 (1.9–2.4)	24% (20%–28%)	17% (14%–20%)

Fractions are pixel-weighted over the group. Changed fraction is $(p_{ls} - p_{st}) / (1 - p_{st})$. Intervals are 95% bootstraps over tiles. Slope-matched and slope-binned statistics are computed at group level from per-slope-class tallies.

With a single limit per tile and all stable ground as the reference, 44.7% of the ground of 3,612 scored landslides in the long window changed beyond the limit against 5.9% of stable ground, an enrichment of 7.6 (Table 3). That is the comparison usually reported, and it overstates the contrast by a factor of two. 65% of the stable ground is gentler than 10° , while 47% of the landslide area is steeper than 30° and 24% steeper than 40° , and the stable-ground exceedance climbs from 4% on the flattest class to 27% above 40° (Table 4, Fig. 3). Re-weighting the stable classes to the landslide slopes gives a floor of 13.7%, an enrichment of 3.3 and a changed fraction of 36%. The slope-binned limit, which rises from 36 cm on flat ground to 116 cm above 40° , brings the stable rate to 5.2% and gives 25%. The event window follows the same pattern at a lower level, 24% with the slope-matched floor and 17% with the slope-binned limit, and does not depend on its worst tiles: without the void-affected tiles, the tiles with limits above 1 m or both,

it gives 25%, 25% and 26%.

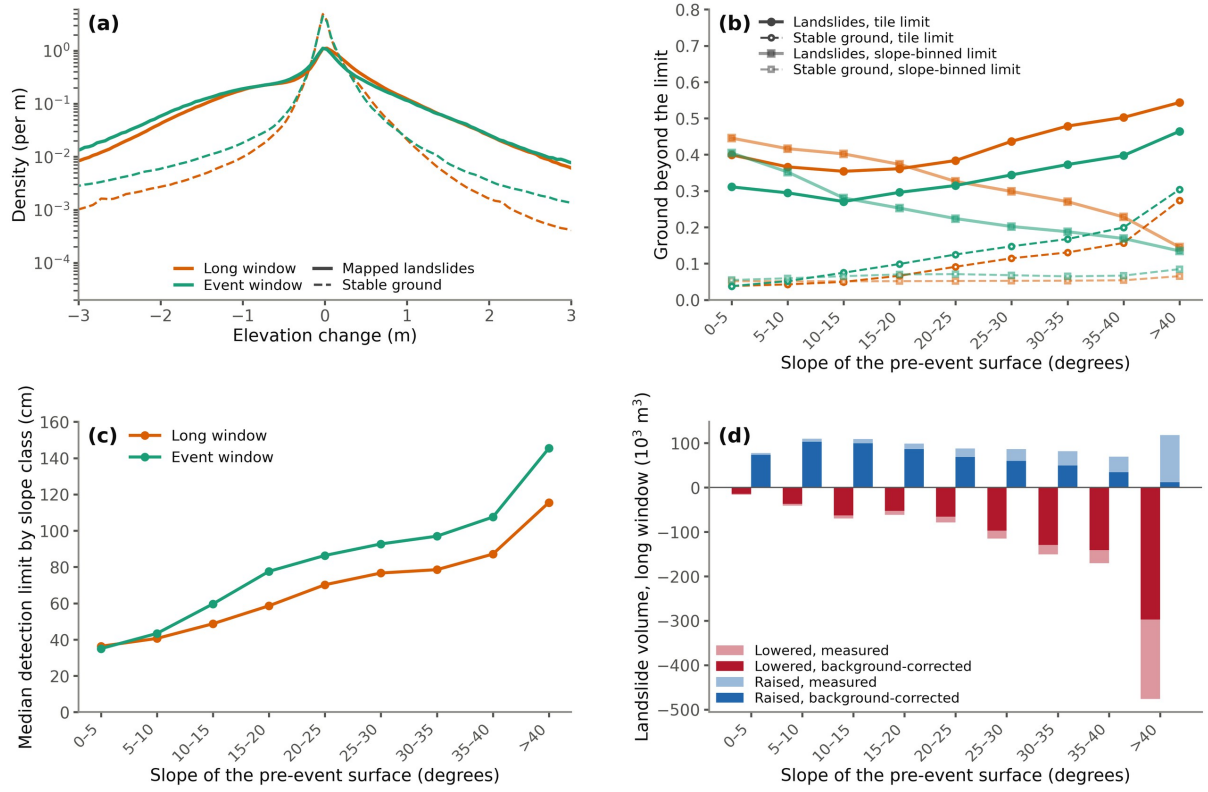


Figure 3. (a) Distribution of the signed elevation change on mapped landslides (solid) and the broad stable class (dashed), long window (orange) and event window (teal), as a density on a logarithmic scale. (b) Fraction of landslide ground (filled markers) and stable ground (open markers) beyond the tile limit (circles) and beyond the slope-binned limit (squares), by slope class. (c) Median detection limit by slope class. (d) Long-window landslide volume lowered and raised by slope class, measured (pale) and after subtracting the stable-ground background volume of the same class (full).

Table 4. Long-window detection, limits and volumes by slope class of the pre-event surface.

Slope (°)	Landslide area (ha)	Stable area (ha)	Landslide beyond tile limit	Stable beyond tile limit	Slope-class limit, median (cm)	Landslide beyond slope-class limit	Lowered, measured / background-corrected (10 ³ m ³)	Raised, measured / background-corrected (10 ³ m ³)
0-5	16	9759	40%	3.8%	36	45%	16 / 14	77 / 74
5-10	29	4190	37%	4.3%	41	42%	41 / 37	110 / 103
10-15	37	2525	35%	5.0%	49	40%	70 / 63	109 / 99
15-20	37	1586	36%	6.6%	59	37%	62 / 53	99 / 86
20-25	38	1043	38%	9.1%	70	33%	79 / 66	87 / 68
25-30	41	812	44%	11.5%	77	30%	115 / 97	86 / 60
30-35	44	706	48%	13.1%	79	27%	151 / 130	82 / 50
35-40	42	460	50%	15.7%	87	23%	170 / 141	69 / 34
above 40	91	486	54%	27.4%	116	15%	476 / 297	118 / 11

Tallies cover all mapped-landslide and broad-stable pixels with valid data in the differenced tiles, so landslide totals exceed those of the 3,612 scored polygons in Section 4.6. Volumes capped at 8 m. Stable ground beyond the slope-class limit is 5.1–6.5% in every class.

Table 5. Landslide and stable ground beyond fixed thresholds, with the stable-ground rate taken over all stable ground and over stable ground re-weighted to the slope distribution of the landslides (slope-matched), and the changed fraction corrected with the slope-matched rate.

Threshold	Long: landslide	Long: stable, all	Long: stable, slope- matched	Long: changed fraction	Event: landslide	Event: stable, all	Event: stable, slope- matched	Event: changed fraction
0.2 m	66.0%	20.1%	33.8%	49%	67.7%	21.7%	41.1%	45%
0.3 m	56.2%	12.5%	23.5%	43%	58.9%	14.0%	30.8%	41%
0.5 m	42.4%	5.8%	13.4%	34%	46.4%	7.8%	19.9%	33%
1.0 m	21.4%	1.6%	4.8%	17%	26.5%	3.6%	9.2%	19%
Tile limit	44.7%	5.9%	13.7%	36%	36.6%	6.6%	17.0%	24%

Changed fraction = (landslide fraction – slope-matched stable fraction) / (1 – slope-matched stable fraction). Fixed-threshold tallies are from the deposited difference and mask rasters with slope from the pre-event surface (thr_by_slope.py); the tile-limit row reproduces Table 3.

At fixed thresholds the stable-ground rate is no longer 5% by construction, but the bias remains: at 0.5 m, 5.8% of all stable ground and 13.4% of stable ground of landslide steepness exceed the threshold in the long window (7.8% and 19.9% in the event window). With the slope-matched floor the changed fraction at 0.5 m is 34% in the long window and 33% in the event window (Table 5), so much of the gap between the windows in Table 3 is a matter of the limit. The signal is strongest in the Senio and Lamone valleys, and reaches on the plain stay near the stable-ground rate (Fig. 4).

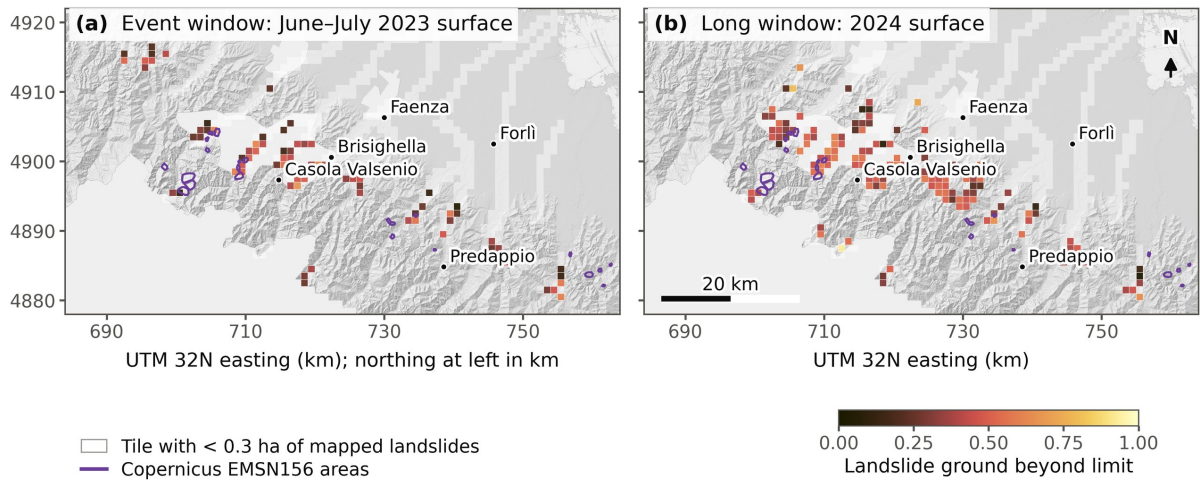


Figure 4. Fraction of mapped-landslide ground in each 1 km tile that changed beyond that tile's detection limit, for the event-window pairs (a) and the long-window pairs (b), on shaded relief. Tiles with less than 0.3 ha of mapped landslides are shown in white; purple outlines are the Copernicus EMSN156 areas of interest.

4.4 The post-event year as a null test

On the 570 triplet tiles, 110 ha of landslide ground is valid in all three differences. In the post-event year the same ground exceeds its limit on 14.5%, against a slope-matched floor of 14.2% and an all-stable rate of 6.1% (Fig. 5a); a tile bootstrap puts the excess over the floor at -1.9 to $+2.9$ percentage points and the ratio to the all-stable rate at 2.0–2.8. Against all stable ground, the landslides would show a ratio of 2.4 in a year in which, against stable ground of their own steepness, they show no excess. On all 579 pair-D

tiles the landslide rate is 14.6%, slightly below a floor of 15.7%, against 6.5% for all stable ground. The agreement holds in both families of triplets, 11.8% against 12.9% on the RER 2023–24 tiles and 16.8% against 17.0% on the RER 2022 tiles, which hold 61 of the 110 ha. In the event and long windows the same ground exceeds the limit on 35% and 45%, against floors of 15% and 15%.

The agreement holds in aggregate, not class by class (Fig. 5b, c). In pair D landslide exceedance hardly varies with slope, from 12% to 17%, while stable exceedance rises from 4% to 25%. Below 20°, 35% of the landslide area, landslide ground exceeds the limit on 13% against 6.3% of stable ground of the same slopes; above 40° on 17% against 25%. The two contribute +2.3 and –2.3 percentage points to the aggregate excess and cancel. Either the year was not quiet on gentle landslide ground, the toes and deposits, or landslide and stable ground of the same slope carry different noise, steep bare scars being smoother than steep forested risers and gentle disturbed ground rougher than fields; the data do not separate the two. What the test establishes is that the floor is right for the landslide slope distribution as a whole: recalibrated on pair D, it gives a long-window changed fraction of 35.4% or 35.8% against 35.3%, and an event-window one of 23.9% or 24.5% against 23.7% (Fig. 5d). Three limits apply. No excess means no change beyond pair D's own limit, a median of 58 cm. Pair D compares two post-event surfaces and cannot test errors that only pre-to-post pairs carry, such as lowering where the pre-event ground filter kept vegetation or debris. And the test is circular about quietness (Section 3.3).

Ground beyond the limit in both the event window and the post-event year with the same sign is 1.6% of the landslide ground against a floor of 0.7%, and with opposite signs 6.4% against 7.2%: ground that kept changing in the same direction is about one percent of the landslide area. Thresholded volumes are not additive across windows and cannot rank them: raw lowering on the triplet landslides is 397 thousand m³ in the event window and 369 thousand m³ in the long window, and the order reverses after background correction (249 against 272). In pair D the correction returns 10 thousand m³ of lowering and –20 thousand m³ of raising, against 126 and 112 thousand m³ measured, so on landslide ground it removes slightly too much raising.

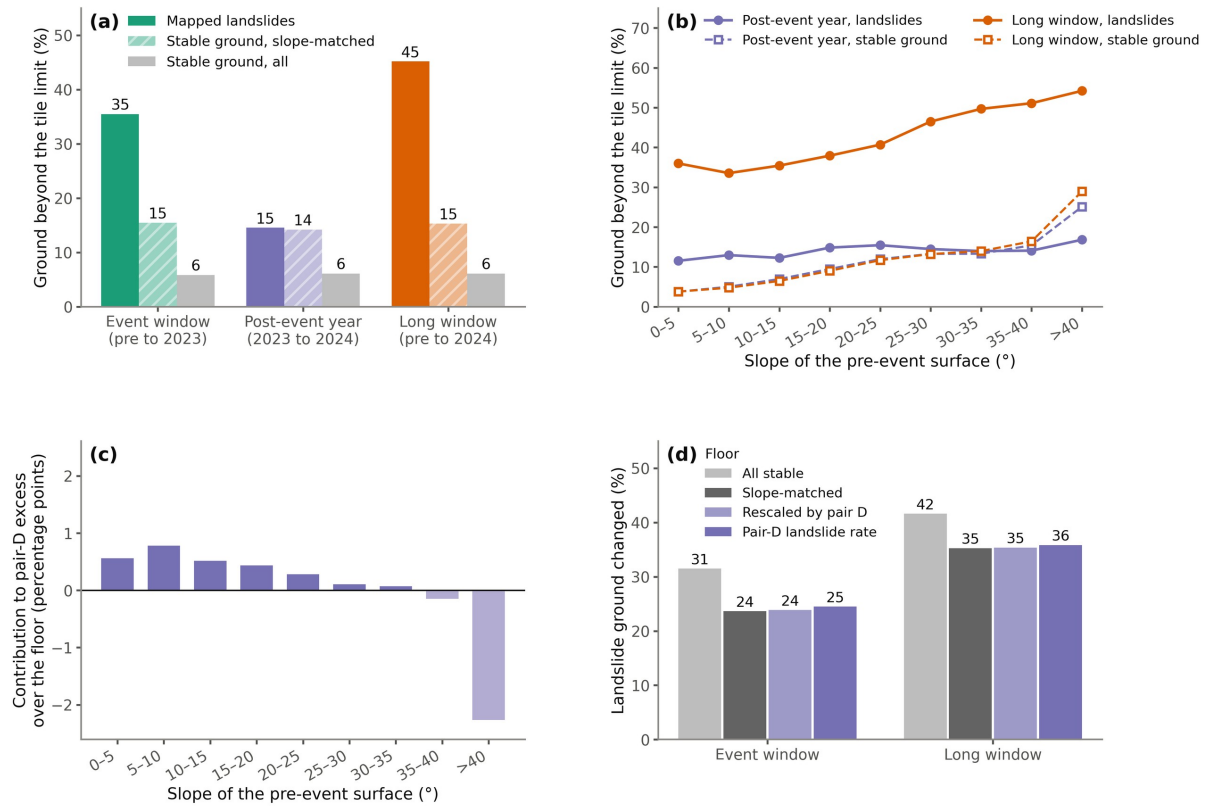


Figure 5. The post-event year as a null test, on the 570 tiles that hold the event-window (E), post-event (D) and long-window (L) differences. (a) Mapped-landslide ground beyond the tile limit, against stable ground of the same slope distribution (slope-matched floor) and all stable ground. (b) Pair D and the long window by slope class of the pre-event surface: landslide ground (filled) and stable ground (open). (c) Contribution of each slope class to the aggregate excess of pair-D landslide exceedance over the slope-matched floor: landslide-area weight times the class difference between landslide and stable exceedance. (d) Changed fraction of landslide ground in the event and long windows with four floors: all stable ground, the slope-matched floor, the floor rescaled class by class by the pair-D ratio of landslide to stable exceedance, and the pair-D landslide rate.

4.5 Size, type and typical landslides

Per landslide the detected fraction under the tile limit has a median of 0.48 in the long window and 0.37 in the event window (Fig. 6a). It is flat with polygon size under the tile limit and under the slope-matched floor, whose per-polygon medians are 0.37–0.39 up to 5,000 m² and 0.33 above. Under the slope-binned limit it rises from 0.17 under 300 m² to 0.26 at 2,000–5,000 m² (Fig. 6b), but that limit removes real change in proportion to slope and small polygons are steeper (median 34° under 300 m² against 25° above 5,000 m²), so the rise belongs to the estimator. A 2.5 m rim inside the outline is detected less than the core only when pixels are pooled (0.24 against 0.30); per polygon the median difference is −0.002 (Table S5).

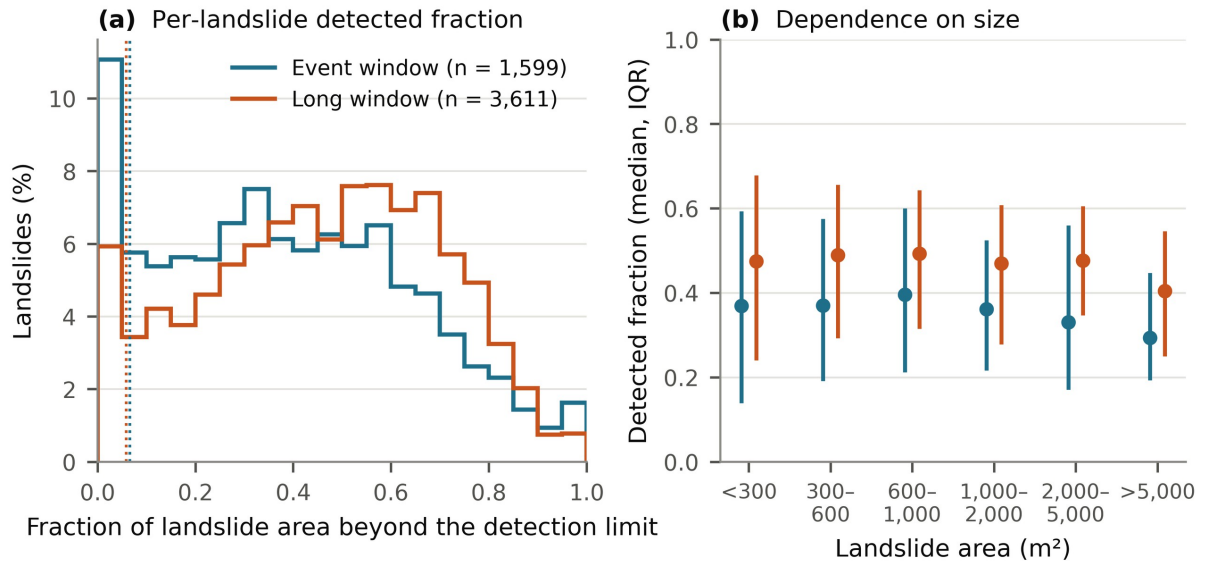


Figure 6. (a) Distribution of the detected fraction per landslide, the fraction of its area with $|dh|$ above the tile detection limit, for the long-window and event-window groups; dotted lines mark the exceedance of all stable ground in each group, dashed lines the slope-matched stable-ground rate. (b) Detected fraction by landslide area: median and interquartile range under the tile limit (circles), median under the slope-binned limit (squares), and the median slope of the long-window polygons in each class (grey line, right axis).

Table 6. Detection and volume by RER2023 landslide type, long-window group, scored polygons.

Class	n	Area (ha)	Median slope (°)	Area above 30°	Median detected fraction, tile limit	Median detected fraction, slope-binned limit	Median, manual class (n)	Lowered / raised (10 ³ m ³ , cap 8 m)
DF1	227	60	26	39%	0.35	0.19	0.35 (334)	145 / 86
DF2	140	27	33	58%	0.50	0.25	0.41 (270)	102 / 53
DS1	2,301	179	35	59%	0.54	0.22	0.57 (1,649)	645 / 403
DS2	79	5	28	33%	0.38	0.21	0.44 (330)	9 / 9
EF	258	40	29	39%	0.23	0.14	0.36 (673)	67 / 37
ES	582	36	30	41%	0.36	0.19	0.34 (331)	81 / 53
RS1	14	19	18	11%	0.62	0.50	0.62 (14)	102 / 94
RS2	11	7	15	5%	0.25	0.35	0.25 (11)	5 / 8

Classes: DS debris slides, DF debris flows, ES earth slides, EF earth flows, RS rock slides, subtypes 1 and 2 as defined by Bertl et al. (2025). The manual-class column groups the same polygons by the original field-based class (ClassMan).

Under the tile limit the types appear to differ widely, from 0.23 for earth flows to 0.54 for debris slides and 0.62 for rock slides, but most of the spread is slope, and 35% of the scored polygons change class between the manual and the harmonised fields (Table 6). Under the slope-binned limit the area-weighted detected fractions of every class except the first rock-slide subtype fall within 0.24–0.29, against 0.53 for RS1; the 11 rock-block slides, eight of them on one tile, are too few to read. Type says little here for two reasons. The slide–flow split is a classification of shape, and the harmonised earth flows, the class detected

least, are its most elongated subset: under the manual class, earth flows have a median of 0.36 ($n = 673$), close to earth slides (0.34) and debris flows (0.35). And the scored earth slides and flows are not the slow earthflows of the Emilia clay shales: 838 of 840 lie in the Pliocene clays of unit 1, the earth flows at a median slope of 29° , in badland terrain where steep bare slopes are rilled every winter; the inventory's earth landslides in the Epiligurian marls and Ligurian clay shales (units 2 and 3; 478 ha, 34% of its earth-landslide area) are absent from the sample. Within debris slides of the first subtype the lithological units differ modestly (Table S9).

Fig. 7 shows four of these landslides in the orthophotos of 2020 and May 2023, the imagery the inventory was mapped on, and in the pre-event and 2024 LiDAR. Where the 2020 images show vegetation, vineyard or grass, the May 2023 images show bare scars and spread debris, and the LiDAR shows the same scars as relief change; inside each outline only part of the ground changed beyond the limit, and the debris-flow outline includes a long runout track with little detectable change. Fig. 8 follows one landslide of each main class along a profile, chosen by rule at the class median detected fraction (Fig. S4 shows eleven whole tiles chosen by rule). The rock slide shows the textbook form, 6 m of lowering at the crown and 4 m of raising over the displaced body and toe. The debris flows show 3–4 m of lowering at the upslope end and about 1 m of raising below it; the earth slide shows 0.9 m of lowering at the upslope end and a body within the limit; the debris slide is lowered within its body; and the earth flow stays within the limit over most of its length. In every case the lowering occupies part of the outline, which Section 4.6 measures.

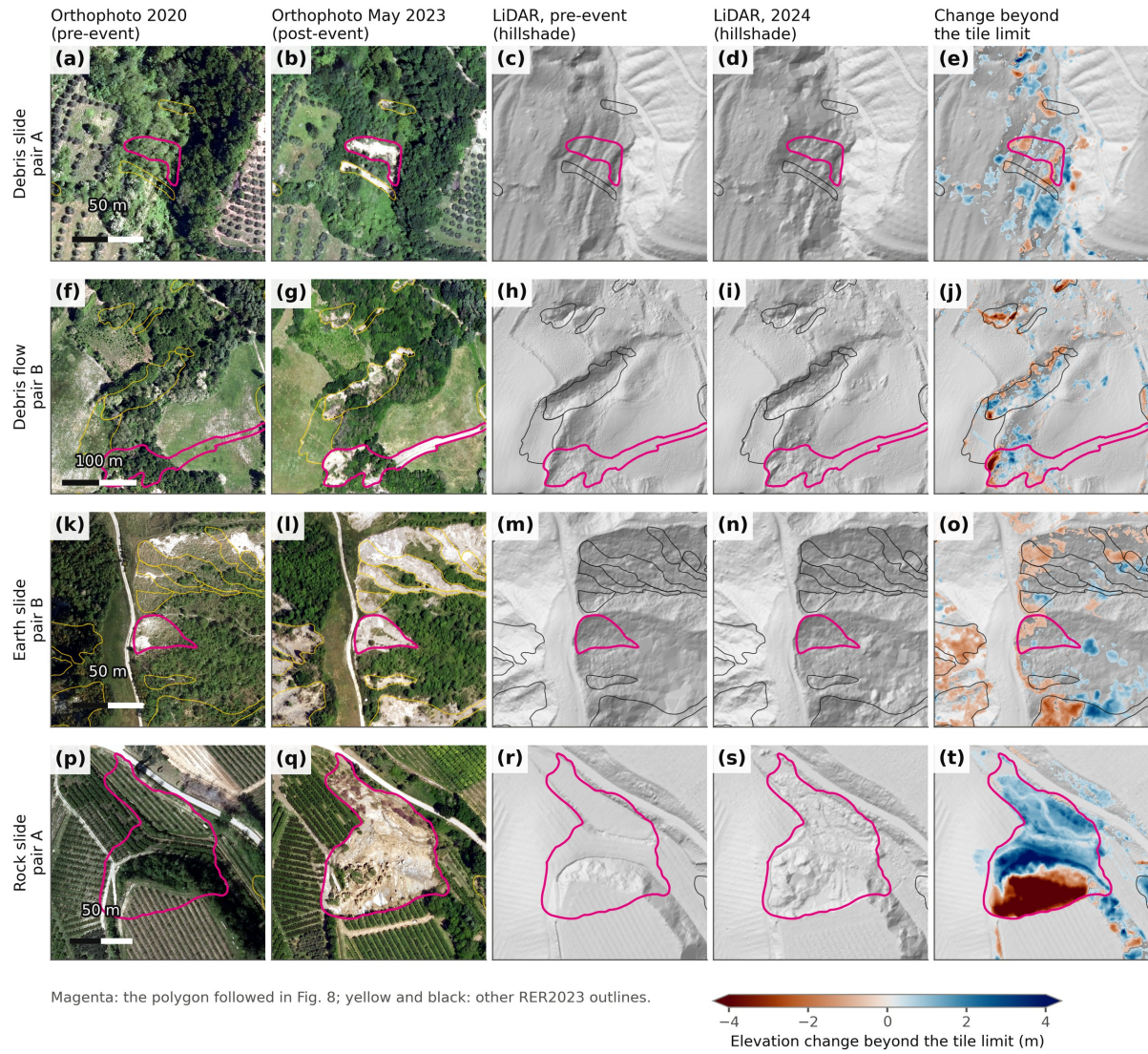


Figure 7. Optical and LiDAR imagery before and after the event at four of the landslides of Fig. 8: a debris slide (a–e, pair A), a debris flow (f–j, pair B), an earth slide (k–o, pair B) and a rock slide (p–t, pair A). Columns: AGEA 2020 orthophoto (pre-event); CGR emergency orthophoto of May 2023 (post-event, 0.2 m), on which RER2023 was mapped; hillshade of the pre-event LiDAR surface; hillshade of the APC Fiumi 2024 LiDAR surface; elevation change beyond the tile limit on the pre-event hillshade. Magenta, the polygon followed in Fig. 8; yellow and black, other RER2023 outlines. Orthophotos © AGEA, served by Regione Emilia-Romagna; LiDAR, Regione Emilia-Romagna (CC BY 4.0).

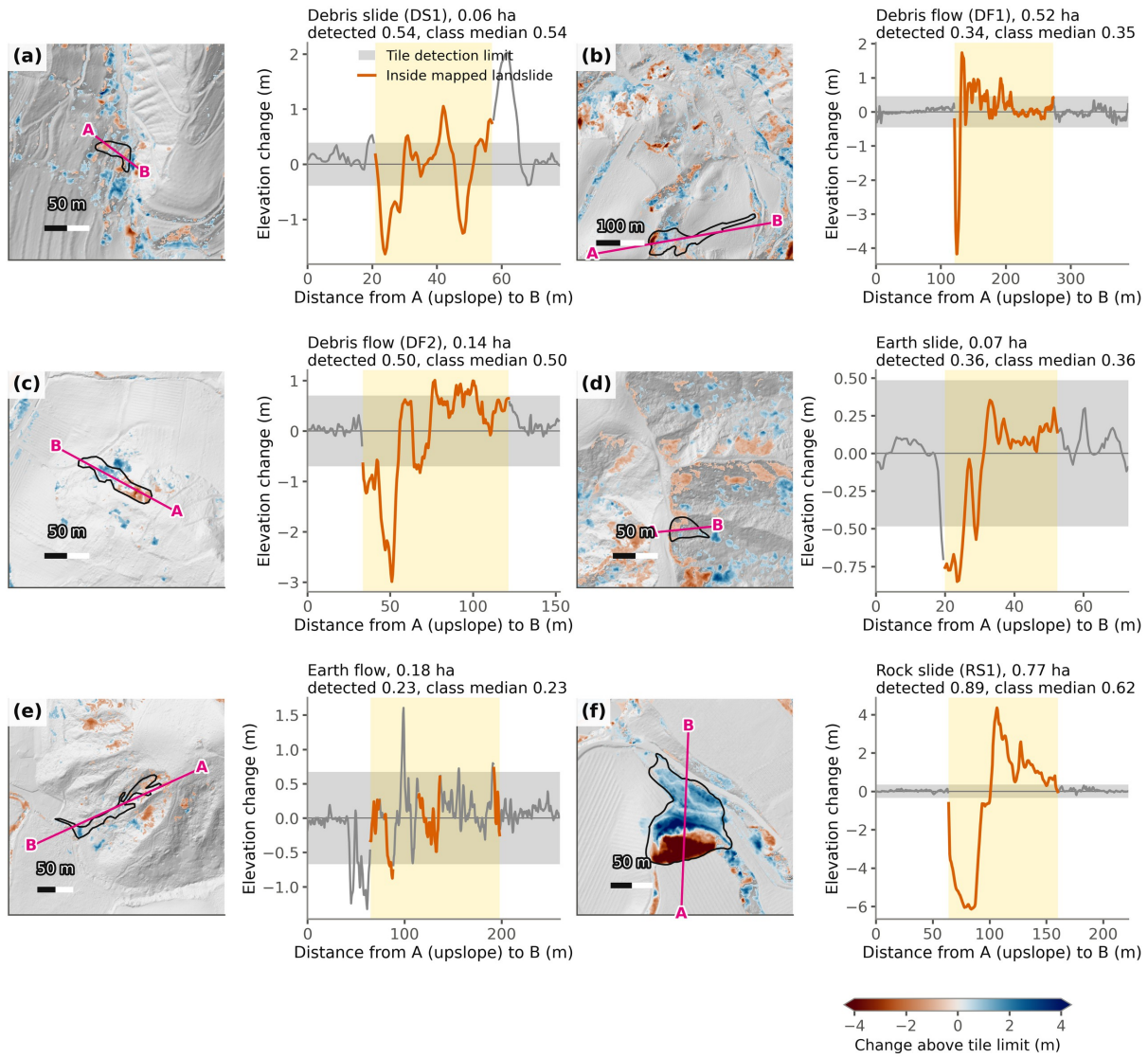


Figure 8. One landslide per main class at the class median detected fraction. Rule: single-tile polygon with at least 95% coverage and area at or above the class median, with detected fraction nearest the class median (for rock slides only three polygons qualify). (a) DS1, polygon 4192, pair A, 0.06 ha, detected 0.54 (class median 0.54); (b) DF1, polygon 38198, pair B, 0.52 ha, detected 0.34 (class median 0.35); (c) DF2, polygon 14058, pair B, 0.14 ha, detected 0.50 (class median 0.50); (d) ES, polygon 36364, pair B, 0.07 ha, detected 0.36 (class median 0.36); (e) EF, polygon 14011, pair B, 0.18 ha, detected 0.23 (class median 0.23); (f) RS1, polygon 3260, pair A, 0.77 ha, detected 0.89 (class median 0.62). Left of each pair: change above the tile limit on shaded relief of the pre-event surface, with the polygon outlined and the profile A–B along its long axis, A at the upslope end. Right: change along A–B; grey band, tile limit; yellow band, inside the polygon.

4.6 Volumes, lowered areas and area–volume scaling

Summed over the 3,612 scored long-window landslides, 1,155 thousand m^3 of ground was lowered and 743 thousand m^3 raised beyond the tile limit, with per-pixel changes capped at 8 m. The background is 24.0% of this gross volume (26% over all landslide pixels of Table 4), 76% of it on slopes above 30° (Fig. 3d). It is not symmetric noise: on flat ground raising exceeds lowering two to one and above 40° the reverse, the signature of fill and tillage on the plain and of bank and riser erosion on steep ground. Because pair D shows the correction removing slightly too much raising, while the threshold and the cap bias the

measured volume low (UAV-measured depths of the event's shallow landslides are of the order of the limit; Schilirò et al., 2025), the corrected volumes are central estimates with errors of either sign. The random, spatially correlated uncertainty (Rolstad et al., 2009), applied to the polygons as if they formed one area, is ± 55 thousand m^3 , an indicative figure because the polygons are scattered across the corridors and the volume is thresholded. Thresholded lowering exceeds thresholded raising, but by a ratio that depends on the threshold, and the unthresholded net change on the polygons, corrected for the mean stable-ground difference of each slope class, is -0.07 m over the mapped area in the long window against -0.06 m in the post-event year. The mass balance of the polygons is therefore not resolved to better than about 0.05 m, and we draw no sediment budget from it, although debris and wood certainly left them for the rivers (Berti et al., 2025).

Table 7. Area lowered beyond a threshold, lowered volume and area–volume scaling on the scored debris and earth landslides (rock slides excluded).

Window and threshold	Polygons	Lowered share of mapped area (range over noise models)	Lowered volume (10^6 m^3)	Scaling on mapped area / lowered volume	Scaling on lowered area / lowered volume	Mean lowering over lowered area (m)	Exponent, least squares / reduced major axis
Long window, 0.2 m	3,587	23% (23% to 34%)	0.87	10.3	1.4	1.09	1.11 / 1.22
Long window, 0.3 m	3,587	22% (22% to 30%)	0.86	10.4	1.3	1.11	1.12 / 1.22
Long window, 0.5 m	3,587	19% (19% to 25%)	0.81	11.1	1.1	1.21	1.13 / 1.23
Long window, tile limit	3,587	20% (20% to 26%)	0.82	11.0	1.2	1.18	1.13 / 1.23
Long window, 1.0 m	3,587	10% (10% to 13%)	0.55	16.3	0.7	1.55	1.10 / 1.19
Event window, tile limit	1,590	16% (16% to 24%)	0.17	15.4	1.4	0.88	1.16 / 1.41
Post-event year (control), tile limit	1,417	-6% (-6% to 5%)	-0.07	—	—	—	—

Noise removed alike from area and volume with the stable-ground model (Section 3.4); the range covers no removal and removal rescaled by the post-event year. Scaling: $V = 0.074 A^{1.450}$ (Guzzetti et al., 2009), on the full polygon area and on the lowered area pro-rated to it. Exponent of lowered volume on lowered area for polygons with at least 25 m^2 lowered. In the post-event year the corrected lowered area and volume are negative, so ratios and exponents are not defined.

Only part of each outline was lowered (Table 7, Figs. 7 and 9). At the tile limit 20% of the mapped area of the 3,587 scored debris and earth landslides was lowered beyond it (20% to 26% over the noise models), 13%–22% across size classes and 10% to 34% across thresholds from 1.0 to 0.2 m. The lowering sits upslope: a median 85% of the lowered pixels lie in the upper half of each polygon by pre-event elevation. In the post-event year the same estimator finds none: the corrected lowered area is -5.7% of the mapped area and the lowered volume -0.07 million m^3 , and the lowered pixels show no upslope concentration

(46% in the upper half). The event window, with higher limits, gives 16%. Rock slides, 14% of the long-window lowering and mostly displacement, are excluded from what follows.

Applied to the mapped outlines, the relation of Guzzetti et al. (2009) predicts 11.0 times the lowered volume at the tile limit (95% tile-bootstrap interval 9.6–12.5; 8.1–11.0 over the noise models), 7.5 to 16.3 times across thresholds and noise models, and 15 times in the event window (Fig. 9a). Applied to the lowered area, it predicts 1.18 times the lowered volume (1.06–1.32), but this ratio moves from 0.69 to 1.61 with the threshold, because the lowered area shrinks faster than the lowered volume as the threshold rises. The relation was fitted to whole-landslide areas and volumes, so its agreement with the lowered ground at one threshold tests nothing; its exponent can be tested.

The exponent of lowered volume on lowered area is 1.13 by least squares at the tile limit (95% interval 1.10–1.16), 1.07–1.14 for area cutoffs of 10 to 500 m², and 1.23 by reduced major axis; across thresholds and noise models it is 1.06–1.15 by least squares and 1.09–1.26 by reduced major axis, and 1.16 in the event window (Fig. 9c). The estimator lowers exponents, because the thin margins of a source fall below the threshold: in simulation true values of 1.00, 1.15, 1.30 and 1.45 return 1.00, 1.13, 1.25 and 1.36. The observed values therefore correspond to a true exponent of about 1.1 to 1.3, below the 1.45 of the relation and within the 1.1–1.3 usual for soil landslides (Larsen et al., 2010); Massey et al. (2020) found 0.92–1.06 on digitised source areas of coseismic soil avalanches at Kaikōura and 1.46–1.47 for slides that kept their mass in the source. The mean lowering over the lowered area, 1.2 m at the tile limit, is set largely by the threshold (1.1–1.6 m from 0.2 to 1.0 m) and is not a source depth. Because the exponent is below 1.45, the relation applied to lowered areas underestimates the lowering of small polygons (0.06 against 0.12 million m³ under 500 m²) and overestimates that of the largest (0.10 against 0.04 above 1 ha; Fig. 9d).

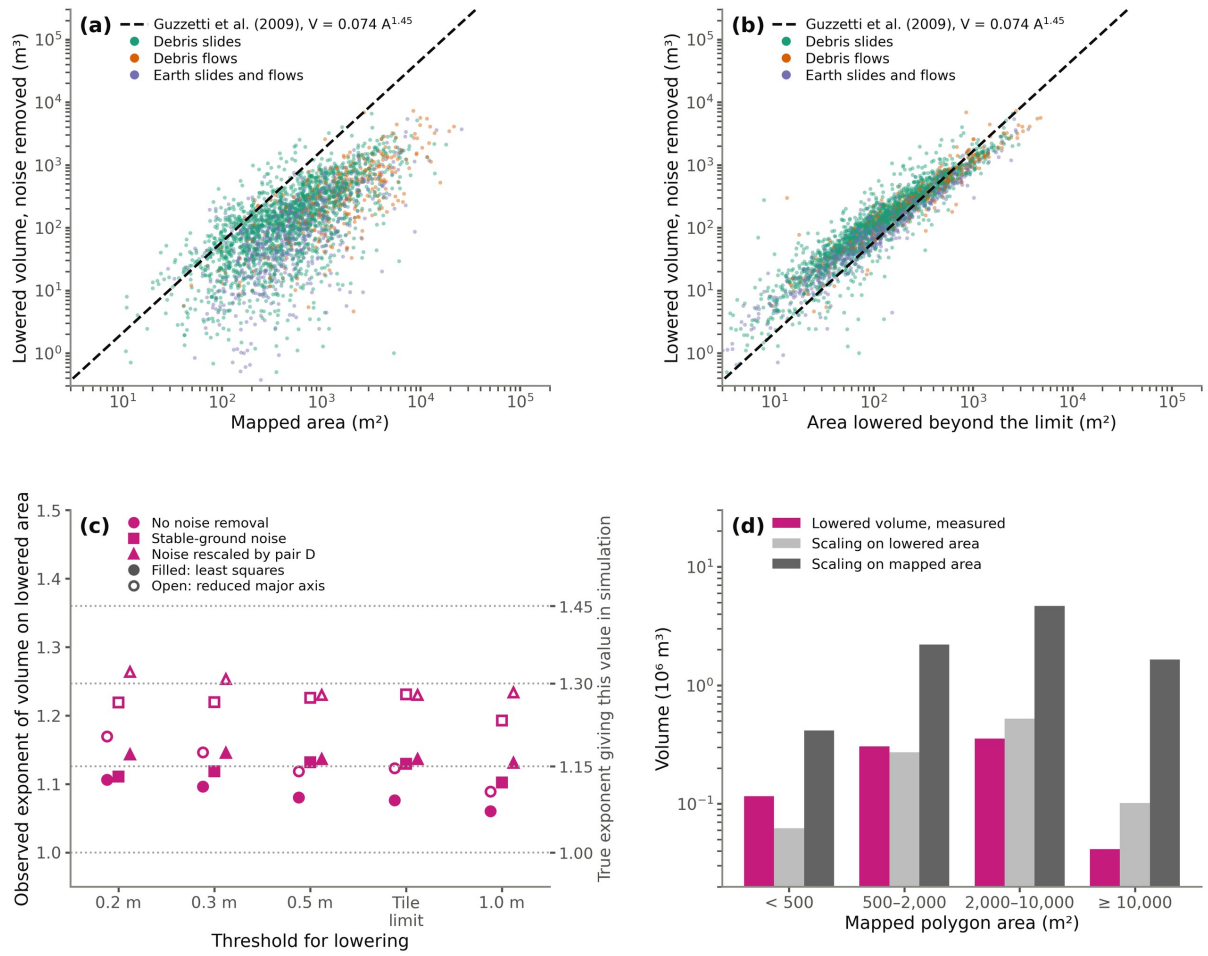


Figure 9. Lowered area and area–volume scaling on the 3,587 scored long-window debris and earth landslides, with noise removed alike from area and volume. (a) Lowered volume against mapped area and (b) against the area lowered beyond the tile limit, coloured by landslide type; dashed, $V = 0.074 A^{1.45}$ (Guzzetti et al., 2009). (c) Exponent of lowered volume on lowered area (polygons with at least 25 m² lowered) by threshold and noise model, by least squares on log mean lowering (filled) and by reduced major axis (open); dotted lines and right axis, the value the estimator returns in simulation for true exponents of 1.00 to 1.45. (d) Lowered volume and the relation applied to the lowered and to the mapped area, summed by mapped polygon area.

4.7 Comparison with EMSN156

Six EMSN156 areas of interest (1–4, 10 and 11) have polygons on the RER 2022 block. Pair A covers 77 polygons (27.4 ha) under the inclusion rule; our thresholded volumes are 0.74 of EMSN156 erosion and 0.68 of its accumulation (0.82 and 0.77 unthresholded), and polygon by polygon the two agree in rank ($r = 0.84$ in log space, $n = 72$; Fig. S7a). On the 50 polygons covered by both pairs the erosion ratio is 0.83 for pair A and 0.81 for the same-month pair A2, and 0.91 and 0.93 unthresholded (Fig. S7b): LiDAR lowering is about four fifths of the photogrammetric estimate, mostly because of the limit. Accumulation is 0.80 and 0.64, but one 12.7 ha slide, covered on 52% of its area, sets the total, and on the other 49 the ratios are 0.67 and 0.23; we draw no conclusion from accumulation. Per polygon the median ratio of our gross volume to EMSN156’s is 0.51 (interquartile range 0.33–0.75), so the totals are carried by the larger slides, and the two estimates share the RER 2022 surface, so they are not independent.

5. Discussion

5.1 Validation needs a slope-matched floor

Any statistic that calibrates a single limit on stable ground and tests it on mapped landslides inherits a bias of this kind, whose size depends on the slope distributions of the stable ground and of the landslides; here the enrichment falls from 7.6 to 3.3 when the floor is slope-matched. The post-event year turns the argument into a measurement: in aggregate, an all-stable reference reports a 2.4-fold signal where the slope-matched floor reports none, and a floor recalibrated on that year changes the result by under one point. The support is aggregate. Class by class, landslide and stable ground of the same slope do not carry the same exceedance, so a floor matched on slope alone is right for a landslide population, not for a slope class within it, and studies that compare classes or areas of different steepness should test the floor on each. We recommend that inventory-validation studies report the slope distribution of their stable ground and the slope-matched floor beside the usual enrichment, and check the floor on a window with little expected change where one exists.

5.2 Inventory volumes need lowered or source areas

Rainfall inventories map the whole disturbed footprint, which is right for hazard and for validation but the wrong area for volume. Here about a fifth of the mapped area of debris and earth landslides was lowered beyond half a metre, mostly in the upper half of each polygon, and the relation of Guzzetti et al. (2009) applied to the outlines overstates the measured lowering 8- to 11-fold at the tile limit. Two consequences follow. Area–volume relations should be applied to source or lowered areas, or to outlines only with a measured lowered fraction, which LiDAR differencing supplies for every polygon at once wherever pre-event coverage exists. And their exponent should be checked against the event: here it lies between about 1.1 and 1.3, so a relation with 1.45 moves volume from small to large landslides even where its total is of the right order. Neither the lowered area nor its mean depth is a source property independent of the threshold, and both should be reported with it.

For the inventory as a whole the corridor sample gives an order of magnitude, not a budget. Multiplying the corridor mean lowering (0.26 m over the scored area after background correction) by the 8,383 ha mapped gives about 22 million m³, and a stratified estimator changes this by under 1%, but the sample does not span the inventory: 94% of the scored area lies between 700 and 745 km easting against 61% of the inventory, the sample holds 0.9% of its area west of 700 km where the inventory has 10%, and none east of 760 km where it has 8%; 39% of the inventory area lies in 10 km blocks with no scored polygon, and the earth landslides of the Emilia marls and clay shales are absent. An event budget would need repeat coverage of the upper slopes and of Emilia, or a model-based estimator with lithology, land cover and slope as covariates.

5.3 A mapping programme is not a monitoring programme

Three generations of regional LiDAR, 14,000 km² of tiles and no ground covered by all three is not an oversight: each contract was scoped to extend coverage. The 204 tiles re-flown after the storm exist as

flight-log entries, not as data, because the programme publishes one merged surface per tile, as most do. Keeping every pass with its acceptance status costs storage, and a planned repeat block of 500–1,000 km² over the hazard belt every two or three years would add 4–9% to the area the main survey has delivered and give every future event a recent pre-event surface beyond the river corridors. The Dutch programme repeats the whole country every three to five years (Shi et al., 2025), and only four European countries have mapped their territory more than once (Moudrý et al., 2026).

5.4 Limits

The pre-event surfaces are three days to fourteen months old, so the two May pulses are not separated and pre-event creep on known earthflows is included. The post-event surfaces follow rivers, so the sample is the lower, Romagna part of the inventory, dominated by the Marnoso-Arenacea flysch and the Pliocene clays; the slope bias and the lowered-area result are properties of the method and the failures and should transfer, but the changed fraction and the volumes describe that part only. The detection limit censors thinning below about half a metre, so the lowered area depends on the threshold and the fitted exponent is biased low, which the simulation quantifies under independent noise only. Slope is computed over a 1 m baseline and partly measures roughness, and the stable-ground noise rates overstate landslide lowering on steep ground and understate it on gentle ground (Section 4.4), hence the three noise models. The 2023 emergency surface carries facets and fills that the mask only partly catches, and the facet-mask thresholds were not varied, so event-window volumes are indicative only. Nothing in the pipeline is specific to Emilia-Romagna: it needs two bare-earth grids on a common tile scheme and a polygon inventory.

6. Conclusions

1. A single detection limit per tile, calibrated on stable ground, is exceeded by noise on 4% of flat ground and 27% of slopes above 40°; because mapped landslides are steep, the stable rate that applies to them is 13.7%, not 5.9%, and the usual comparison doubles the apparent signal.
2. A pair spanning the first post-event year is consistent with the slope-matched floor in aggregate (14.5% against 14.2%, where all stable ground gives 6.1%); gentle and steep classes depart in opposite directions and cancel, and a floor recalibrated on this pair changes the result by under one point.
3. With the corrected floor, 36% of mapped landslide ground in the river corridors changed beyond the limit (25% with a slope-binned limit); ground that kept changing in the same direction in the following year is about one percent of it.
4. Only 20% (20% to 26% over noise models) of the mapped area of debris and earth landslides was lowered beyond the tile limit, mostly in the upper half of each polygon, and the estimator finds no lowering in the post-event year. Area–volume scaling applied to the outlines overstates the measured lowering 8 to 11 times at the tile limit; on lowered areas the exponent is about 1.1 to 1.3, not 1.45.
5. Once slope is controlled, detection is flat with polygon size and differs little between landslide types other than rock slides; LiDAR erosion is about four fifths of the EMSN156 photogrammetric estimate, mostly because of the limit.

6. Three regional LiDAR generations overlap on under 1% of their area and re-flown passes are served as one merged surface; keeping every pass and flying a planned repeat block would move the programme from mapping to monitoring.

7. Data and code availability

Data availability. All input data are public: the DTMs by Web Coverage Service (dtmrer2022, dtmrer2023_24, dtm_cgr_emg_fiumi_202305, dtm_apc_fiumi_2024) and the tile indices by the metadata_raster map service of Regione Emilia-Romagna (CC BY 4.0); the AGEA 2020 and CGR May 2023 orthophotos by Web Map Service of Regione Emilia-Romagna (agea2020_rgb, cgr_emg_202305_rgb; © AGEA); the RER2023 inventory v1 from Zenodo (doi 10.5281/zenodo.13742643, CC BY 4.0); the regional administrative inventory from the regional geoportal (CC BY 3.0); the EMSN156 geodatabase and volume rasters from the Copernicus Emergency Management Service. The LiDAR catalogue (39 surveys, with an evidence link per fact), the exact overlap polygons, the tile lists, the per-tile results of the five pairs, the three-surface tallies, the difference and mask rasters of every tile-pair, pair D included (about 12 GB), the per-landslide tables including unscored polygons, the slope-class tallies, the area–volume table, the 25 m slope surface and the extrapolation strata, the EMSN156 comparison table and every figure are available from the author on request (smeena@ogs.it) and will be published on Zenodo with a persistent identifier.

Code availability. The tile-selection, batch-differencing, aggregation and figure scripts (Python 3.11; numpy, scipy, rasterio, geopandas, matplotlib) are released with the data, on the same terms. One command per pair reproduces its run from the public services; pair D, the three-surface pass, the null-test bootstrap, the depletion pass and the extrapolation run from the cached surfaces in under an hour on a workstation.

8. Supplementary material

The supplementary material at the end of this preprint holds Tables S6 (the seven audited surveys), S7 (scored and unscored polygons), S8 (pairwise overlaps) and S9 (lithology within debris slides), and Figures S1 (flight-log classification of the RER 2023–24 tiles), S2 (three tiles in both windows), S3 (detection limit against NMAD), S4 (eleven tiles chosen by rule), S5 (detected fraction by landslide type), S6 (map of change over the central belt) and S7 (comparison with EMSN156). Tables S1 (the 39-survey catalogue), S2 (per-tile results), S3 (EMSN156 per polygon), S4 (results by comune) and S5 (rim and core per polygon) are spreadsheets available from the author on request.

CRedit authorship contribution statement

Sansar Raj Meena: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing.

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Declaration of competing interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author used Claude (Anthropic) to assist with code drafting, with checking references against Crossref, and with drafting the text. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Supplementary material: Mapping landslide change and volume with repeat airborne LiDAR after the May 2023 Emilia-Romagna event: slope-dependent detection limits and lowered areas

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Table S6. The seven LiDAR surveys audited or differenced.

Survey	Owner (contractor)	Flight window	Tiles	Area in region (km ²)	Stated accuracy (1 σ)
RER 2022	Regione (CGR)	9 Feb 2022 – 14 Jan 2023, six blocks	1,823	1,433.7	DTM 8 cm vertical, 30 cm horizontal
RER 2023–24	Regione (CGR), Leica TerrainMapper, 8 pts/m ²	23 Mar 2023 – 13 Jan 2025; 9,240 km ² planned	11,803	11,278.3	sensor < 5 cm / < 13 cm; DTM 8 cm / 30 cm
RER 2025–26	Regione (CGR), same specification	3–12 Apr 2025 so far	1,562	1,441.4	as RER 2023–24
Comune di Bologna 2023	Comune (CGR)	19–26 Jun 2023	654	141.1	not published
Comune di Modena 2024	Comune (CGR)	17 May – 5 Jun 2024	1,152	263.5	not published
CGR emergency corridors 2023	CGR, post-event emergency flight	2 Jun – 18 Jul 2023, 23 river corridors	no index	≈ 639	not published
APC Fiumi 2024	APC	13 Mar – 17 Jun 2024, 24 river sectors	1,036 in study area	943	not published

Tile counts and areas are from the live tile indices (metadati_raster map service, layers 30, 44, 61, 49, 51 and 40), queried on 11 October 2026; areas are the union of tile polygons clipped to the region. The emergency corridors of 2023 have no tile index in the service; their area is the figure in the catalogue. The RER 2023–24 index carries up to five flight dates per tile; the RER 2022 index one date string per tile; APC Fiumi 2024 up to five dates and two tile-naming schemes.

Table S7. Scored and unscored RER2023 polygons in the long-window tiles.

Set	Polygons	Median area (m ²)	DS1	DF2	ES	EF	Lithology 1	Lithology 7
scored	3,612	450	64%	4%	16%	7%	23%	69%
unscored	6,395	447	51%	5%	21%	13%	33%	59%

Shares of each class among the polygons of the set. Scored: at least half the polygon has valid data on both surfaces. The share of polygons scored is 41% for DS1, 31% for ES and 23% for EF.

Table S8. Pairwise overlap of the audited surveys (km²).

Overlap (km ²)	RER 2023–24	RER 2025–26	Bologna 2023	Modena 2024
RER 2022 (1,433.7)	30.3	0.9	0.0	0.0
RER 2023–24 (11,278.3)	—	0.5	1.6	109.6
RER 2025–26 (1,441.4)	—	—	0.0	0.0

Footprint areas in km² are in brackets.

Table S9. Detection by lithological unit within debris slides of the first subtype (DS1), long-window group, units with at least 40 scored polygons.

Lithological unit (Berti et al., 2025)	n	Area (ha)	Median slope (°)	Median detected fraction, tile limit	Median detected fraction, slope-binned limit	Area-weighted, slope-binned limit
4 (coarse-grained unit)	41	3	32	0.41	0.16	0.29
6 (coarse-grained unit)	55	3	32	0.44	0.21	0.29
7 (Marnoso-Arenacea Formation (Miocene flysch))	2,098	163	35	0.55	0.23	0.27
8 (coarse-grained unit)	107	9	33	0.53	0.27	0.32

Unit codes and names follow Table 1 of Berti et al. (2025): units 1 to 3 are fine-grained (clays and clay shales), units 4 to 8 coarse-grained (flysch and sandstones). The harmonised class assigns debris or earth material from the unit at the polygon centroid, so earth slides and flows occur only in units 1 to 3 and debris slides and flows only in units 4 to 8; a lithology comparison is therefore meaningful only within a material class.

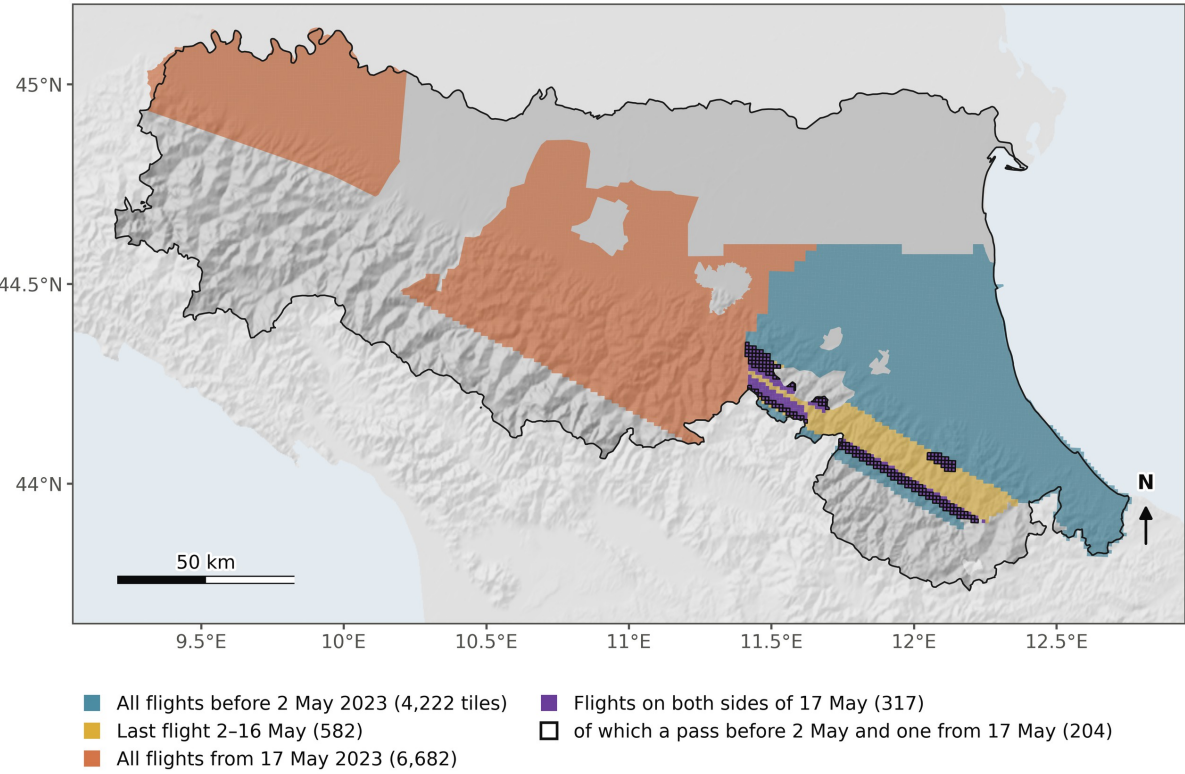


Figure S1. Flight-log classification of the 11,803 RER 2023–24 tiles: tiles flown only before 2 May 2023 (blue), with last flight between the pulses (gold), flown only from 17 May 2023 (orange), and flown on both sides of 17 May (purple); the 204 tiles with a pass before 2 May and another from 17 May are outlined.

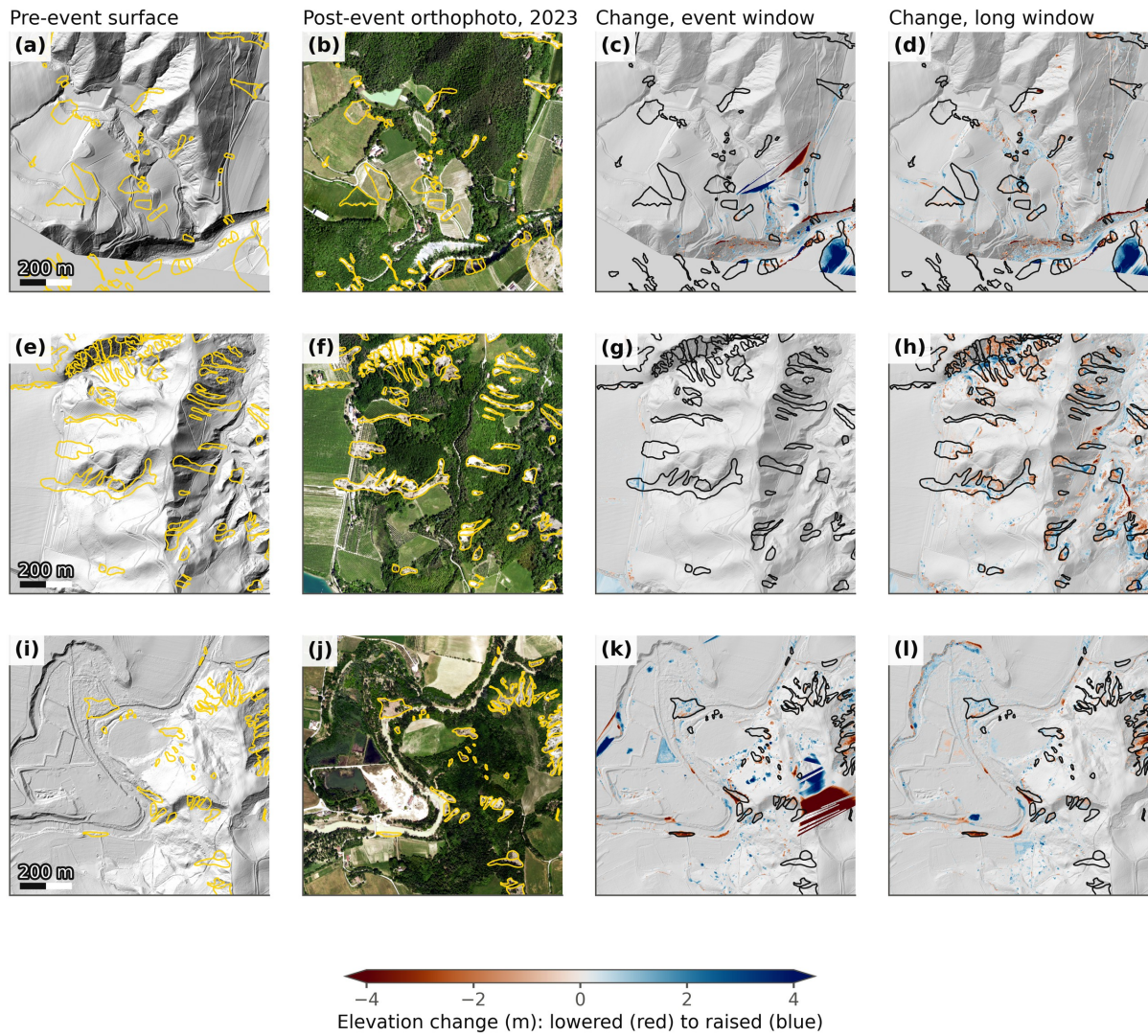


Figure S2. Three 1 km tiles. Columns: shaded relief of the pre-event surface; the emergency orthophoto of 2023; elevation change above the detection limit in the event-window pair; and in the long-window pair. RER2023 polygons are outlined. Ground without valid data on either surface, including masked planar facets, shows the shaded relief only; the flat grey area in the first row lies outside the pre-event surface. Row 1, tile 32_70804898 (pairs A2 and A), where a planar facet of the 2023 surface that the mask did not catch appears as a red and blue wedge in panel c; row 2, tile 32_72604896 (pairs C and B), where the 2023 surface covers only the river strip, so the event-window panel shows almost no change; row 3, tile 32_74504887 (pairs C and B), where a smooth void fill in the 2023 surface (panel k, lower right) is only partly masked and shows as a lowering of metres that the 2024 surface does not have.

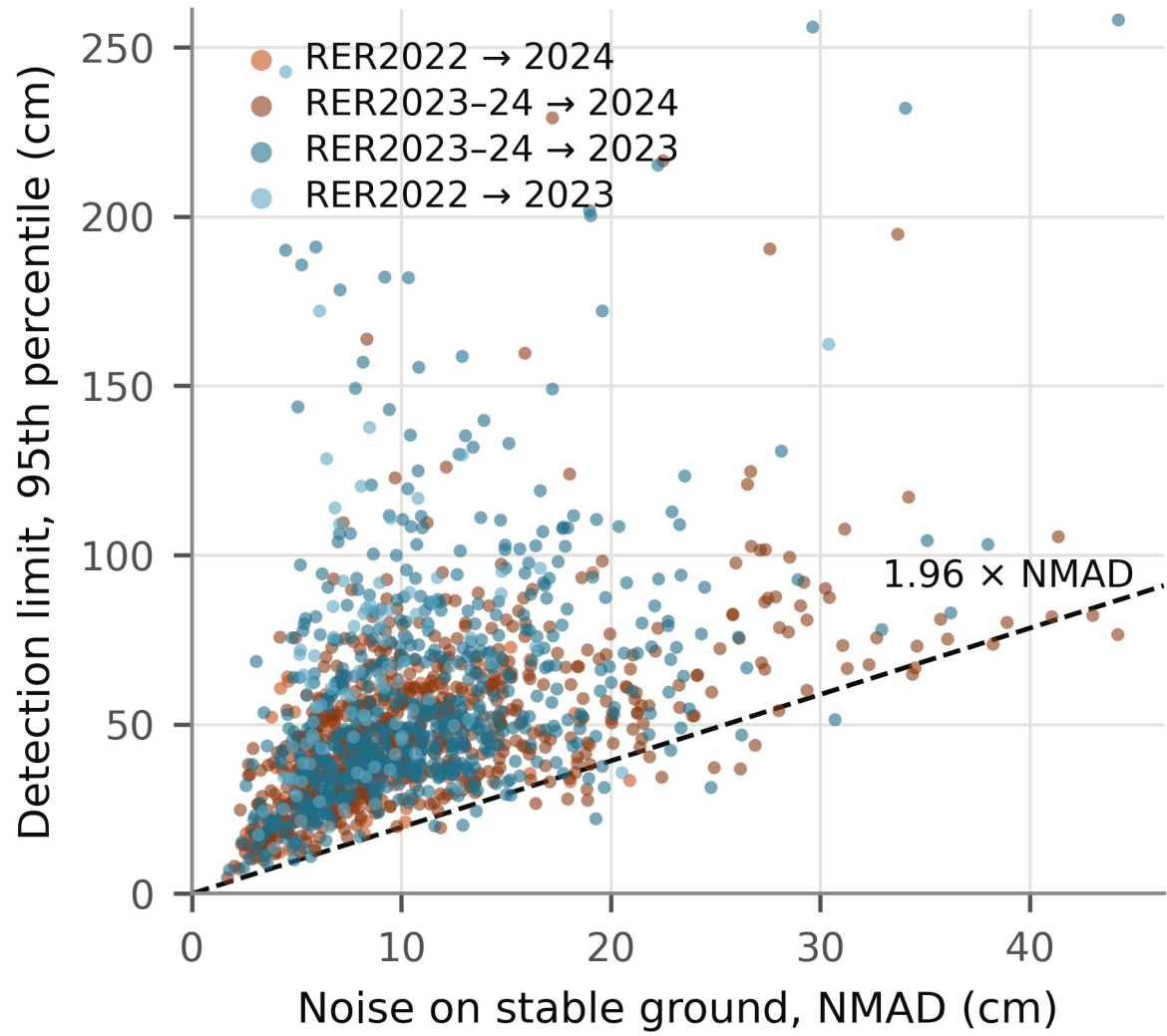


Figure S3. Empirical 95th-percentile detection limit against the NMAD of the stable-ground difference, one point per tile, by pair. The dashed line is the Gaussian relation, $1.96 \times \text{NMAD}$.

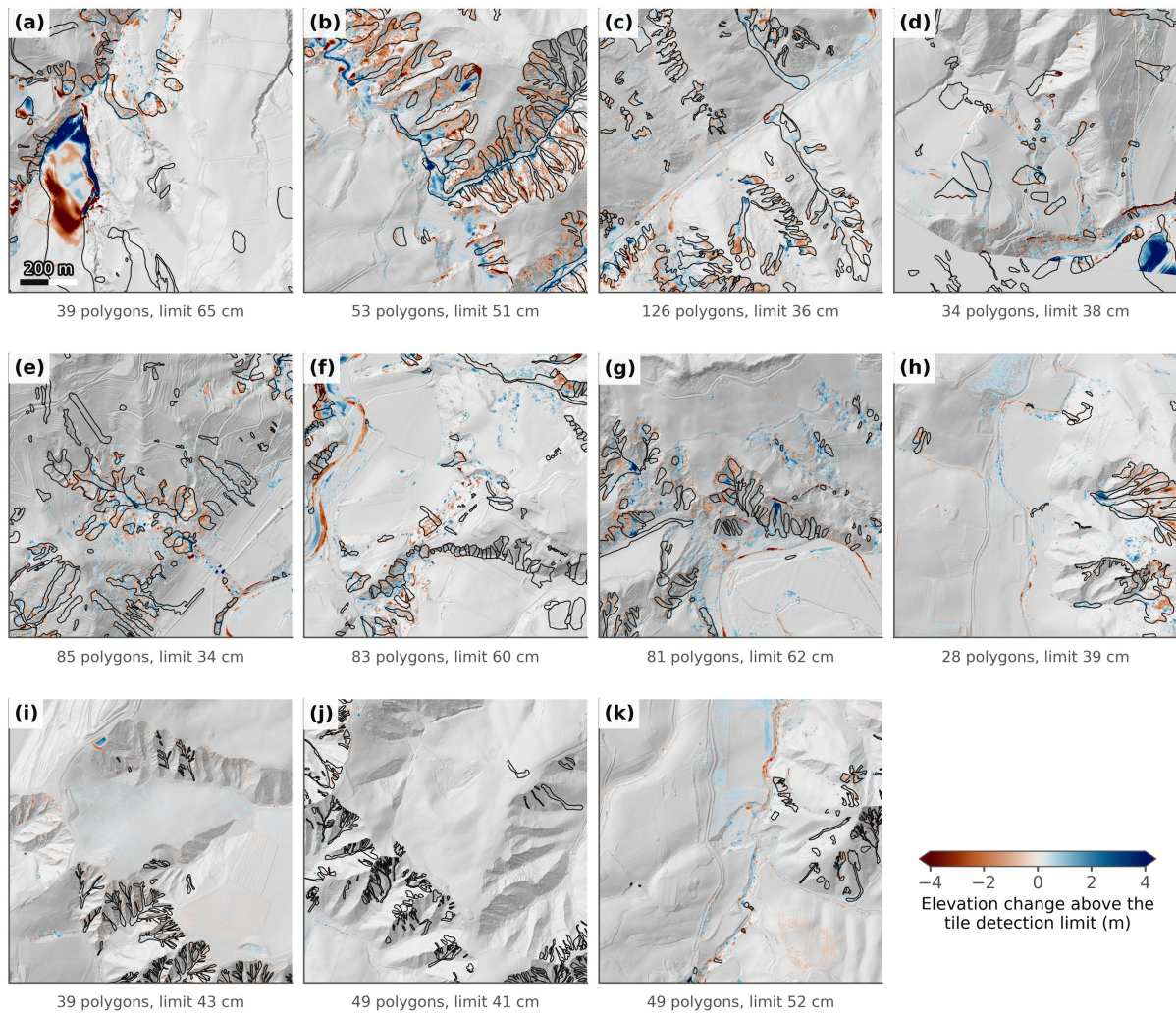


Figure S4. Eleven long-window tiles chosen by rule. (a)–(h) the eight tiles with the largest capped gross volume on scored polygons, with at least 20 scored polygons and at least 3 km apart: (a) 32_70704902 (pair A), (b) 32_72704895 (pair B), (c) 32_73004894 (pair B), (d) 32_70804898 (pair A), (e) 32_71904899 (pair A), (f) 32_71204902 (pair A), (g) 32_70404905 (pair A), (h) 32_73104898 (pair B); (i)–(k) the three tiles with at least 30 scored polygons and the smallest difference between landslide and stable-ground exceedance, no spacing rule, (j) and (k) adjacent: (i) 32_71504907, (j) 32_73204896, (k) 32_73104896. Elevation change above the tile limit on shaded relief of the pre-event surface (ground without valid data on either surface shows the relief only; flat grey is outside the pre-event surface); RER2023 polygons outlined; the number of scored polygons and the tile limit are given under each panel.

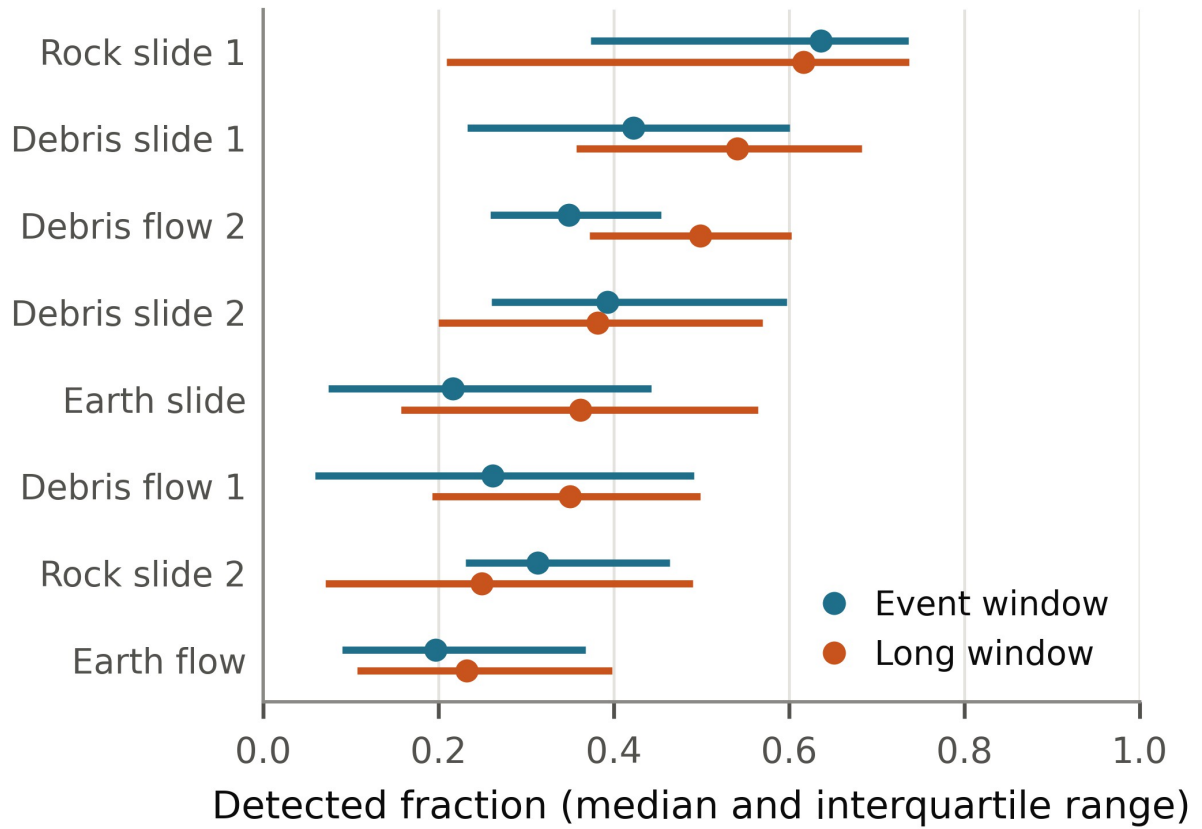


Figure S5. Detected fraction by RER2023 landslide type, median and interquartile range, for the long-window group (orange) and the event-window group (teal). Detected fractions are under the tile limit; see Table 6 for the slope-binned values.

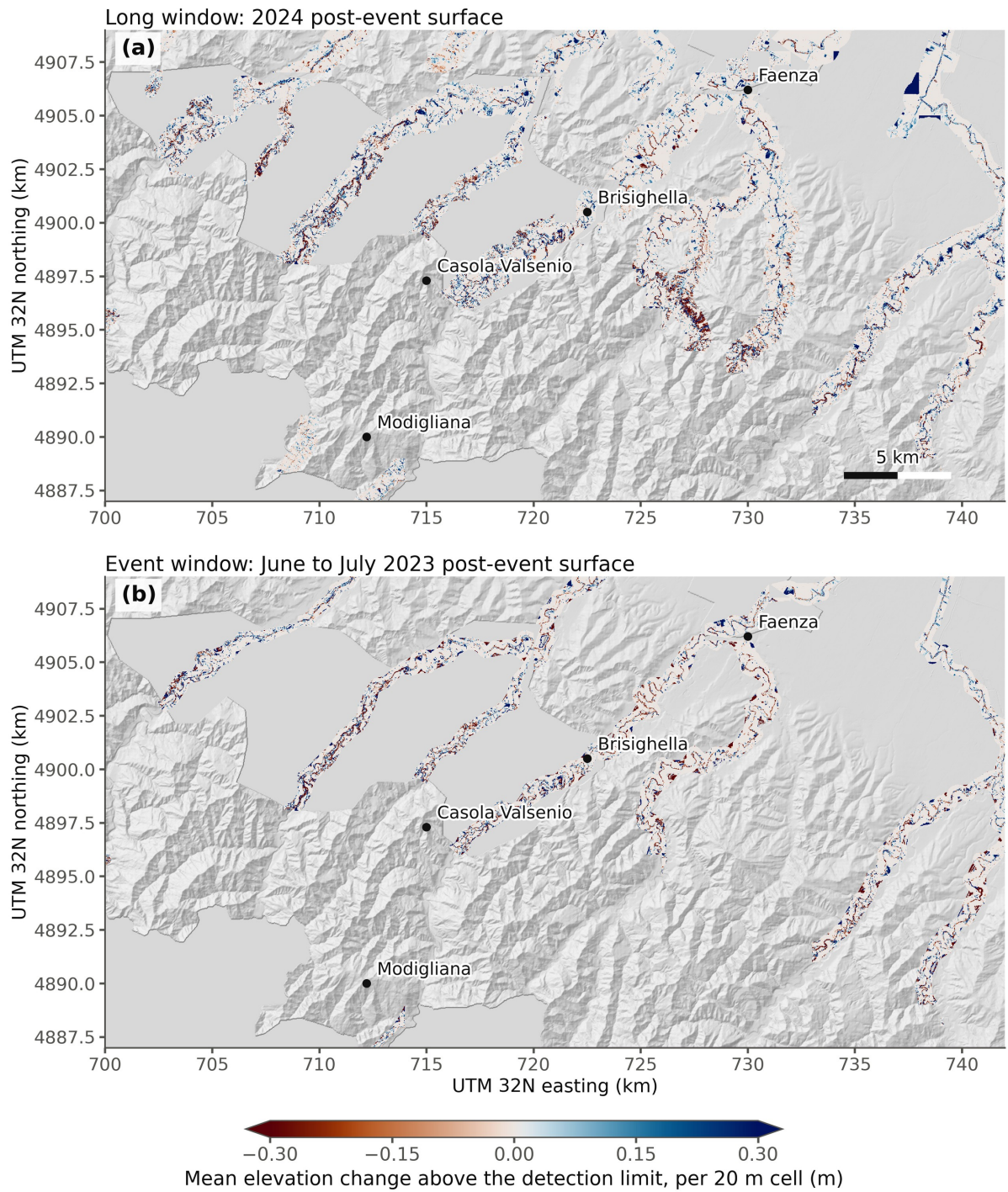


Figure S6. Elevation change above the detection limit across the Romagna Apennines, averaged in 20 m cells (mean over all valid ground in the cell, so cells with change on part of their area are paler). (a) Long window: pairs A and B, post-event surface from 2024. (b) Event window: pairs C and A2, post-event surface from June to July 2023. Where two pairs of a group cover a tile, the one with more valid ground is shown.

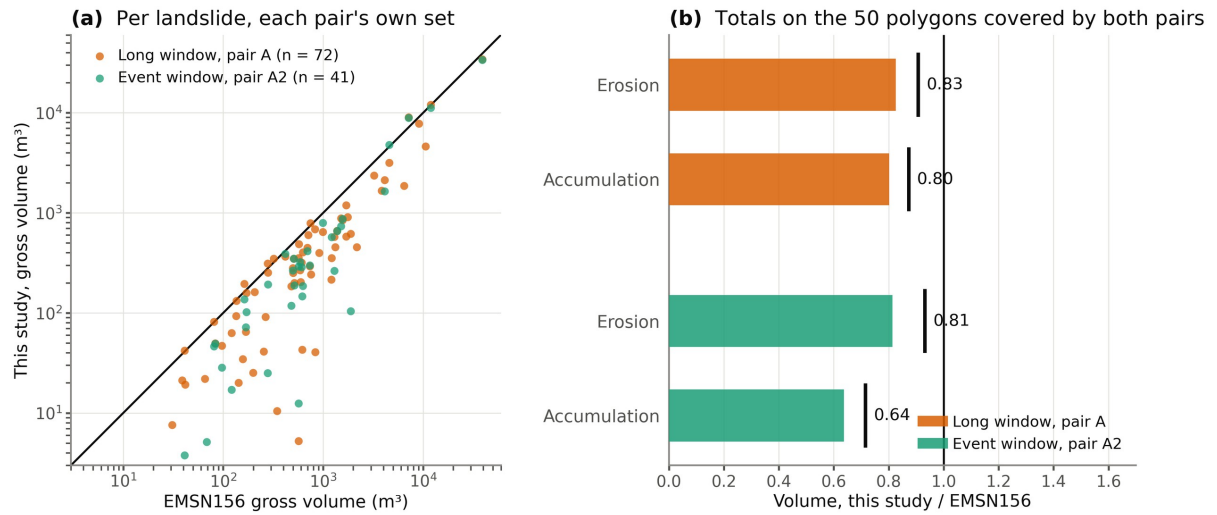


Figure S7. Comparison with the Copernicus EMSN156 volumes on every polygon with at least half of its area covered by a pair. (a) Gross volume per landslide, EMSN156 against this study, for the long-window pair A (72 polygons with non-zero volume in both) and the same-month pair A2 (41); the line is 1:1. (b) Ratio of our erosion and accumulation to EMSN156's on the 50 polygons covered by both pairs; bars use the detection limit, ticks are unthresholded.