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Supplement of

A photogrammetry-based approach for soil bulk density measurements with an emphasis on applications to cosmogenic nuclide analysis

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S1 Flower pot design and picturing scenarios

Figure S1. Flower pot design and examples for different settings: (a) D01 – indoors, natural light dominant (tilted); (b) D11 – outdoors, direct sunlight (tilted); (c) D16 – indoors, natural light dominant; (d) D17 – outdoors, direct sunlight; (e) D20 – outdoors, no direct sunlight; (f) D25 – indoors, artificial light dominant. A black/dark brown and white pattern was painted on the initially dark surfaces of the flower pot and the board in order to enhance image textures. The flower pot could be sealed by a thin fabric in order to simulate the pre-dug surface (D11, D16, D20).

S2 BD17 field tests

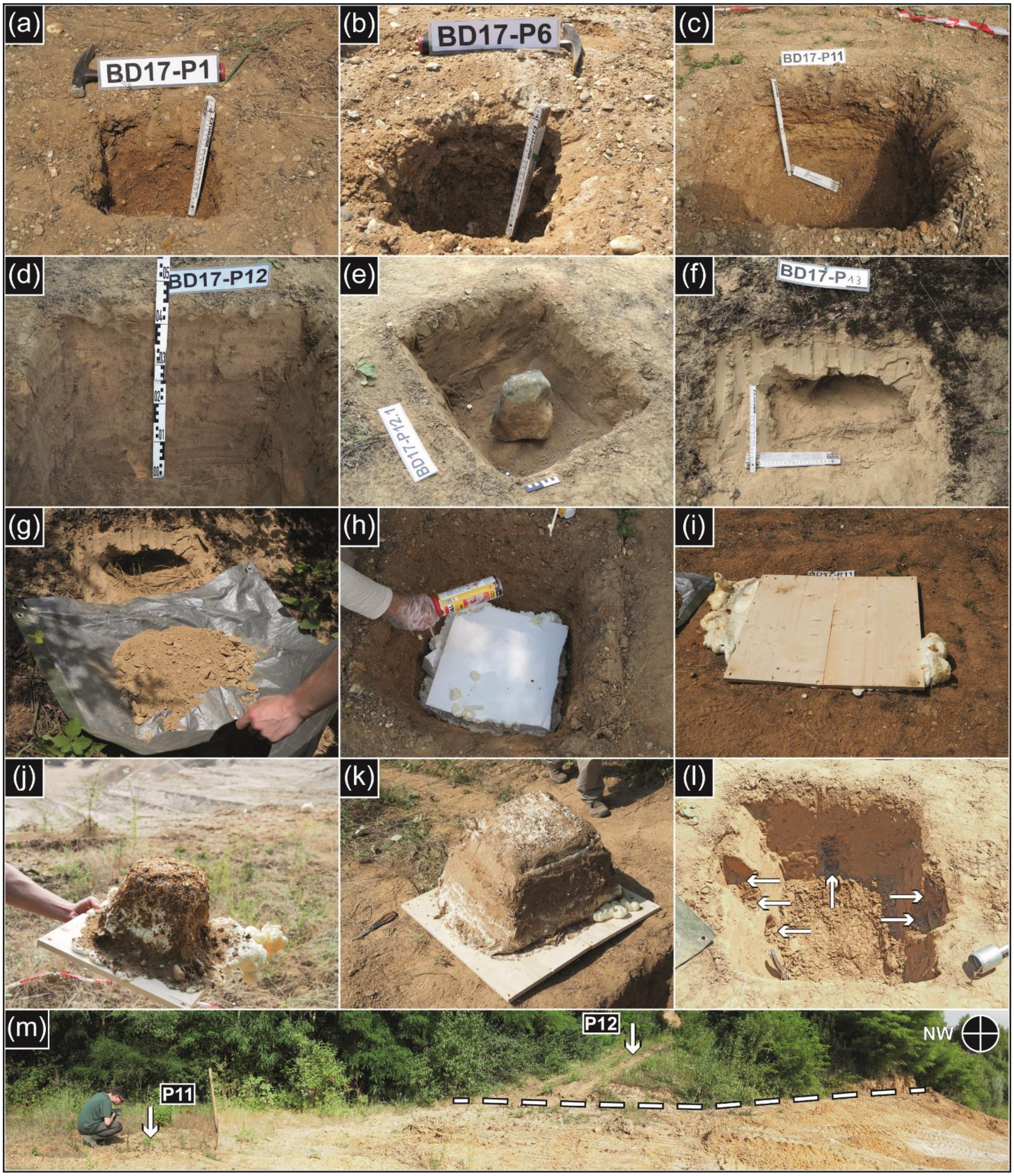

Figure S2. Pictures taken during the field tests in the gravel pit near Cologne, Germany. Different soil pits [(a) – BD17-P01; (b) – BD17-P06; (c) – BD17-P11; (d) – BD17-P12; (e) – BD17-P12.1] and a cavity [(f) – BD17-P13] were dug into gravel and loess layers within a radius of ~50 m. The excavated material was collected on a tarp (g) and weighed afterwards using a digital spring balance (luggage scale). The pits were filled with polyurethane foam and polystyrene blocks in order to obtain casts reflecting the volume of the respective pit after cooling (h-k). Small cores were taken from some sites, including BD17-P12 [(l);

white arrows indicate sampling locations]. Excavation work in the gravel pit has exposed the Pleistocene gravels which are overlain by loess deposits [(m); dashed line indicates the contact between loess (above) and gravel layers (below)].

S3 Altos de Talinay TCN sampling campaign

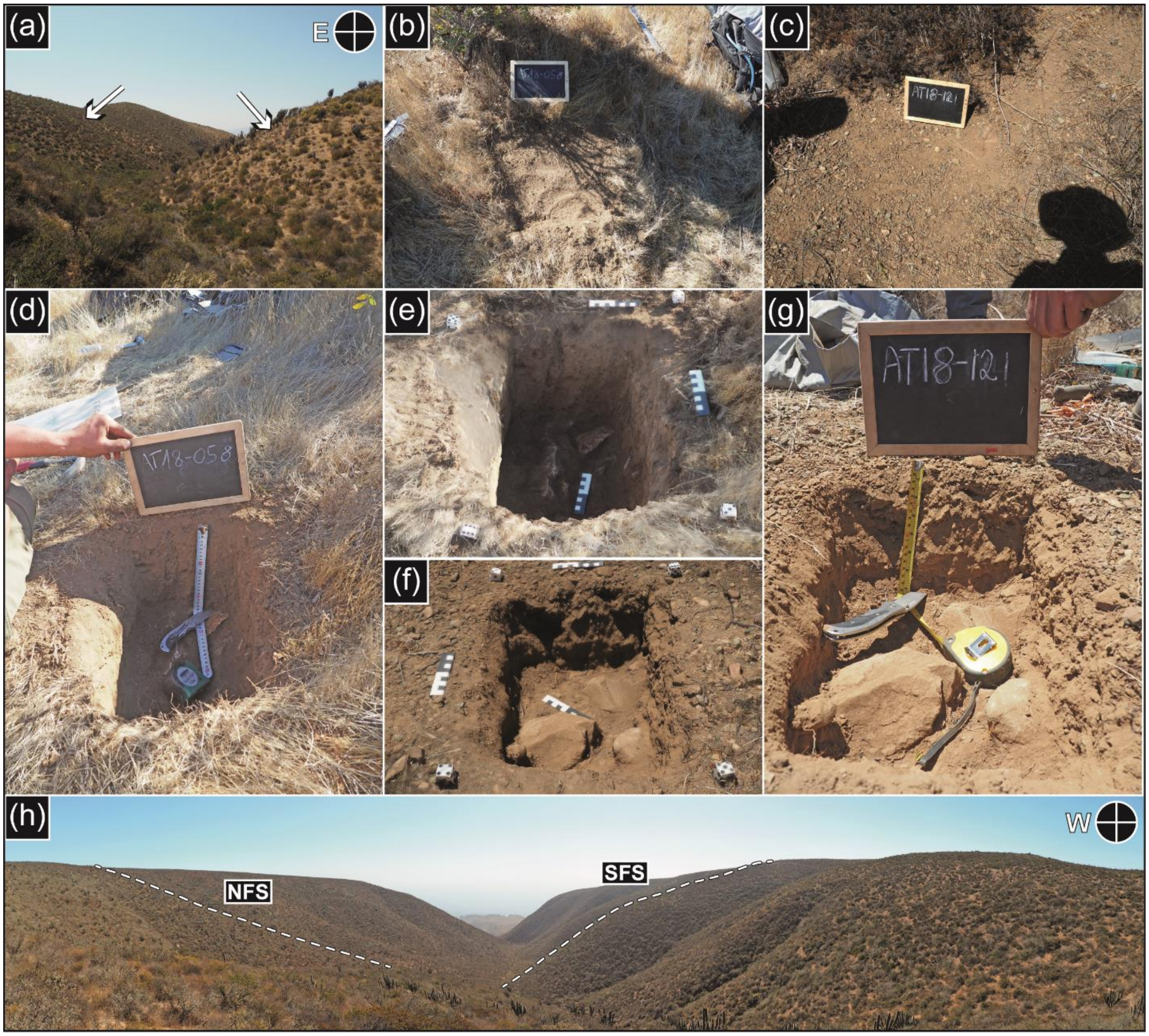

Figure S3. Study area characteristics and examples for sampling sites in the Altos de Talinay, northern central Chile. In the E-W oriented catchments, strong contrasts in vegetation cover and slope morphology between SFS and NFS can be observed (a, h). Before sampling for TCN below the regolith/saprolite or bedrock boundary, pictures were taken from the pre-dug surface [SFS – (b); NFS – (c)]. After sampling, the procedure was repeated by acquiring photographs from the sampling pits [SFS – (d); NFS – (g)]. The image datasets were then used to model the pits [(SFS – (e); NFS – (f)].

Table S1. Sample details and calculated field-state bulk densities of the AT17/18 sampling campaign.

Sample ID	Location (°)		Elevation (m a.s.l.)[a]	Catchment	Exposition	z (cm)[b]	$m_{e,f}$ (g)[c]	Number of pictures	V_{SfM} (cm³)[d]	$\rho_{B,f}$ (g cm⁻³)[e]
AT17-001(1)	-30.4613	-71.6522	338	C1	Ridgetop	22	11150 ± 71	35	8559 ± 70	1.30 ± 0.01
AT17-002	-30.4623	-71.6546	325	C1	Ridgetop	19	10500 ± 71	35	7327 ± 70	1.43 ± 0.02
AT17-023	-30.4610	-71.6486	368	C1	South	10	5000 ± 71	27	3630 ± 70	1.38 ± 0.03
AT17-024	-30.4616	-71.6487	359	C1	South	6	6150 ± 71	45	4143 ± 70	1.48 ± 0.03
AT17-025	-30.4622	-71.6487	344	C1	South	23	10800 ± 71	34	7574 ± 70	1.43 ± 0.02
AT17-026	-30.4627	-71.6489	323	C1	South	28	33250 ± 71	43	36463 ± 70	0.91 ± 0.00
AT17-027	-30.4632	-71.6492	296	C1	South	22	44500 ± 100	91	30164 ± 70	1.48 ± 0.00
AT17-028(1)	-30.4660	-71.6487	387	C1	Ridgetop	5	10950 ± 71	42	8562 ± 70	1.28 ± 0.01
AT17-029(1)	-30.4658	-71.6499	367	C1	North	8	8650 ± 71	80	6940 ± 70	1.25 ± 0.02
AT17-030	-30.4653	-71.6498	360	C1	North	9	9100 ± 71	70	6740 ± 70	1.35 ± 0.02
AT17-031	-30.4647	-71.6498	344	C1	North	6	9750 ± 71	75	6377 ± 70	1.53 ± 0.02
AT17-032TS	-30.4643	-71.6502	324	C1	North	5	3400 ± 71	59	2028 ± 70	1.68 ± 0.07
AT17-033	-30.4638	-71.6499	304	C1	North	2	2800 ± 71	36	1721 ± 70	1.63 ± 0.08
AT18-034	-30.4663	-71.6092	486	C2	North	10	25050 ± 100	29	15654 ± 70	1.60 ± 0.01
AT18-036	-30.4661	-71.6093	480	C2	North	9	9550 ± 71	27	6279 ± 70	1.52 ± 0.02
AT18-037	-30.4658	-71.6093	463	C2	North	15	19550 ± 71	32	13064 ± 70	1.50 ± 0.01
AT18-038	-30.4655	-71.6093	451	C2	North	24	26700 ± 100	35	15255 ± 70	1.75 ± 0.01
AT18-039	-30.4652	-71.6093	435	C2	North	21	17850 ± 71	31	11373 ± 70	1.57 ± 0.01
AT18-040	-30.4653	-71.6093	440	C2	North	30	28550 ± 100	34	17107 ± 70	1.67 ± 0.01
AT18-041	-30.4650	-71.6093	426	C2	North	14	9350 ± 71	46	5662 ± 70	1.65 ± 0.02
AT18-042	-30.4647	-71.6092	409	C2	North	30	29700 ± 100	39	17060 ± 70	1.74 ± 0.01
AT18-044	-30.4642	-71.6090	383	C2	North	23	25600 ± 100	58	18579 ± 70	1.38 ± 0.01
AT18-051	-30.4639	-71.6090	371	C2	North	29	29650 ± 71	42	15525 ± 70	1.91 ± 0.01
AT18-052	-30.4637	-71.6089	358	C2	North	16	18750 ± 71	42	11340 ± 70	1.65 ± 0.01
AT18-053	-30.4634	-71.6098	375	C2	South	24	53400 ± 141	55	34590 ± 70	1.54 ± 0.01
AT18-054	-30.4636	-71.6098	366	C2	South	23	33400 ± 122	44	23699 ± 70	1.41 ± 0.01
AT18-055	-30.4631	-71.6100	404	C2	South	13	21500 ± 71	53	14437 ± 70	1.49 ± 0.01
AT18-056	-30.4628	-71.6103	421	C2	South	25	43500 ± 122	37	35659 ± 70	1.22 ± 0.00
AT18-057	-30.4625	-71.6105	439	C2	South	30	40500 ± 71	40	24884 ± 70	1.63 ± 0.01
AT18-058	-30.4622	-71.6107	455	C2	South	24	42600 ± 122	34	28733 ± 70	1.48 ± 0.01
AT18-059	-30.4632	-71.6099	392	C2	South	23	26950 ± 100	42	18845 ± 70	1.43 ± 0.01
AT18-060	-30.4621	-71.6110	462	C2	South	31	33850 ± 100	70	25213 ± 70	1.34 ± 0.01
AT18-061	-30.4620	-71.6113	468	C2	South	20	30200 ± 100	38	18356 ± 70	1.65 ± 0.01
AT18-062	-30.4618	-71.6115	470	C2	South	20	26900 ± 71	43	17678 ± 70	1.52 ± 0.01
AT18-063	-30.4609	-71.6131	492	C2	Ridgetop	5	10450 ± 71	42	7490 ± 70	1.40 ± 0.02
AT18-102(2)	-30.3922	-71.6474	428	C5	Ridgetop	3	2150 ± 71	35	2356 ± 70	0.91 ± 0.04
AT18-106	-30.3862	-71.6487	455	C5	Ridgetop	22	29600 ± 100	57	20437 ± 70	1.45 ± 0.01
AT18-108	-30.3881	-71.6500	447	C5	South	8	9509 ± 71	38	5757 ± 70	1.65 ± 0.02
AT18-109	-30.3887	-71.6502	442	C5	South	15	27950 ± 71	42	16597 ± 70	1.68 ± 0.01

AT18-111	-30.3890	-71.6502	436	C5	South	10	8200 ± 71	36	5186 ± 70	1.58 ± 0.03
AT18-112	-30.3895	-71.6504	424	C5	South	12	10750 ± 71	78	8015 ± 70	1.34 ± 0.01
AT18-113	-30.3897	-71.6505	415	C5	South	10	8950 ± 71	42	5840 ± 70	1.53 ± 0.02
AT18-114	-30.3899	-71.6506	405	C5	South	11	15350 ± 71	38	11033 ± 70	1.39 ± 0.01
AT18-115	-30.3902	-71.6508	395	C5	South	16	28850 ± 71	72	20737 ± 70	1.39 ± 0.01
AT18-116	-30.3905	-71.6508	378	C5	South	13	16900 ± 71	48	13345 ± 70	1.27 ± 0.01
AT18-117	-30.3908	-71.6509	358	C5	South	19	9650 ± 71	87	8757 ± 70	1.10 ± 0.01
AT18-120	-30.3913	-71.6510	319	C5	South	42	33750 ± 122	38	25663 ± 70	1.32 ± 0.01
AT18-121	-30.3920	-71.6512	321	C5	North	17	22750 ± 71	57	12644 ± 70	1.80 ± 0.01
AT18-122	-30.3923	-71.6510	334	C5	North	13	16850 ± 71	41	9757 ± 70	1.73 ± 0.01
AT18-123	-30.3926	-71.6509	348	C5	North	21	24200 ± 100	39	17393 ± 70	1.39 ± 0.01
AT18-124	-30.3928	-71.6508	363	C5	North	18	19500 ± 71	43	13541 ± 70	1.44 ± 0.01
AT18-127	-30.3935	-71.6504	397	C5	North	16	20400 ± 71	77	15386 ± 70	1.33 ± 0.01
AT18-129	-30.3937	-71.6504	405	C5	North	7	7700 ± 71	55	5881 ± 70	1.31 ± 0.02
AT18-132	-30.3940	-71.6504	416	C5	North	13	11650 ± 71	76	7639 ± 70	1.53 ± 0.02
AT18-133	-30.3943	-71.6504	429	C5	North	7	5650 ± 71	56	4329 ± 70	1.31 ± 0.03
AT18-136	-30.3958	-71.6498	478	C5	North	10	9350 ± 71	38	5429 ± 70	1.72 ± 0.03
AT18-137	-30.3950	-71.6505	457	C5	North	2	1550 ± 71	64	1285 ± 70	1.21 ± 0.09
AT18-138	-30.4001	-71.6510	524	C5	Ridgetop	4	4850 ± 71	62	3489 ± 70	1.39 ± 0.03
AT18-139	-30.3948	-71.6504	448	C5	North	8	8800 ± 71	73	6319 ± 70	1.39 ± 0.02
AT18-145	-30.4613	-71.6487	363	C1	South	20	17900 ± 71	50	13622 ± 70	1.31 ± 0.01
AT18-146	-30.4619	-71.6487	352	C1	South	21	12850 ± 71	54	8929 ± 70	1.44 ± 0.01
AT18-147	-30.4624	-71.6489	336	C1	South	26	19050 ± 71	39	16122 ± 70	1.18 ± 0.01
AT18-148	-30.4629	-71.6491	310	C1	South	14	5850 ± 71	43	5092 ± 70	1.15 ± 0.02
AT18-149	-30.4635	-71.6499	293	C1	North	15	15700 ± 71	83	10571 ± 70	1.49 ± 0.01
AT18-150	-30.4640	-71.6500	313	C1	North	8	5700 ± 71	79	3301 ± 70	1.73 ± 0.04
AT18-151	-30.4645	-71.6500	335	C1	North	14	11350 ± 71	48	8909 ± 70	1.27 ± 0.01
AT18-152	-30.4650	-71.6499	353	C1	North	5	6300 ± 71	82	3848 ± 70	1.64 ± 0.04
AT18-153	-30.4655	-71.6499	365	C1	North	11	13650 ± 71	49	10023 ± 70	1.36 ± 0.01
AT18-154	-30.4658	-71.6495	373	C1	Ridgetop	8	26400 ± 71	50	12482 ± 70	2.11 ± 0.01

[a] *DTM-derived.*
[b] *Soil pit depth below the surface as measured in the field.*
[c] *Field-state excavation mass, uncertainty equals the accuracy of the hand balance used.*
[d] *SfM-MVS photogrammetry-based pit volumes. Uncertainties are 1σ as obtained from the tests performed on the artificial pit.*
[e] *Field-state bulk density.*

Table S2. Sample aliquot measurements and calculated dry densities.

Sample ID	Elevation (m a.s.l.)[a]	Catchment	Exposition	z (cm)[b]	$m_{a,f}$ (g)[c]	$m_{a,d}$ (g)[d]	$m_{a,r}$ (g)[e]	ρ_{BR} (g cm^{-3})[f]	$\rho_{B,d}$ (g cm^{-3})[g]	ρ_d (g cm^{-3})[h]
AT17-001(1)	338	C1	Ridgetop	22	364.1 ± 0.1	360.5 ± 0.1	46.2 ± 0.1	2.82 ± 0.11	1.29 ± 0.01	1.19 ± 0.05
AT17-002	325	C1	Ridgetop	19	204.3 ± 0.1	202.9 ± 0.1	34.1 ± 0.1	2.82 ± 0.11	1.42 ± 0.02	1.29 ± 0.05
AT17-023	368	C1	South	10	468.0 ± 0.1	463.2 ± 0.1	97.7 ± 0.1	2.82 ± 0.11	1.36 ± 0.03	1.20 ± 0.06
AT17-024	359	C1	South	6	224.9 ± 0.1	222.3 ± 0.1	66.6 ± 0.1	2.82 ± 0.11	1.47 ± 0.03	1.22 ± 0.06
AT17-025	344	C1	South	23	363.8 ± 0.1	358.8 ± 0.1	42.4 ± 0.1	2.82 ± 0.11	1.41 ± 0.02	1.32 ± 0.05
AT17-026	323	C1	South	28	457.2 ± 0.1	446.3 ± 0.1	56.6 ± 0.1	2.82 ± 0.11	0.89 ± 0.00	0.81 ± 0.03
AT17-027	296	C1	South	22	619.7 ± 0.1	612.0 ± 0.1	38.3 ± 0.1	2.82 ± 0.11	1.46 ± 0.00	1.41 ± 0.05
AT17-028(1)	387	C1	Ridgetop	5	106.7 ± 0.1	105.5 ± 0.1	10.7 ± 0.1	2.82 ± 0.11	1.26 ± 0.01	1.19 ± 0.05
AT17-029(1)	367	C1	North	8	121.6 ± 0.1	120.3 ± 0.1	7.7 ± 0.1	2.82 ± 0.11	1.23 ± 0.02	1.19 ± 0.05
AT17-030	360	C1	North	9	203.3 ± 0.1	201.9 ± 0.1	42.5 ± 0.1	2.82 ± 0.11	1.34 ± 0.02	1.18 ± 0.05
AT17-031	344	C1	North	6	291.4 ± 0.1	288.9 ± 0.1	51.9 ± 0.1	2.82 ± 0.11	1.52 ± 0.02	1.38 ± 0.06
AT17-033	304	C1	North	2	216.4 ± 0.1	214.8 ± 0.1	76.7 ± 0.1	2.82 ± 0.11	1.62 ± 0.08	1.31 ± 0.10
AT18-034	486	C2	North	10	432.9 ± 0.1	429.9 ± 0.1	35.2 ± 0.1	2.82 ± 0.11	1.59 ± 0.01	1.53 ± 0.06
AT18-037	463	C2	North	15	335.3 ± 0.1	330.0 ± 0.1	74.0 ± 0.1	2.82 ± 0.11	1.47 ± 0.01	1.29 ± 0.05
AT18-038	451	C2	North	24	809.7 ± 0.1	801.2 ± 0.1	282.9 ± 0.1	2.82 ± 0.11	1.73 ± 0.01	1.43 ± 0.06
AT18-041	426	C2	North	14	384.2 ± 0.1	378.6 ± 0.1	94.0 ± 0.1	2.82 ± 0.11	1.63 ± 0.02	1.43 ± 0.06
AT18-051	371	C2	North	29	236.9 ± 0.1	232.8 ± 0.1	65.9 ± 0.1	2.82 ± 0.11	1.88 ± 0.01	1.66 ± 0.06
AT18-053	375	C2	South	24	514.4 ± 0.1	507.4 ± 0.1	97.5 ± 0.1	2.82 ± 0.11	1.52 ± 0.01	1.37 ± 0.05
AT18-056	421	C2	South	25	382.7 ± 0.1	374.7 ± 0.1	62.6 ± 0.1	2.82 ± 0.11	1.19 ± 0.00	1.07 ± 0.04
AT18-058	455	C2	South	24	779.4 ± 0.1	769.3 ± 0.1	180.9 ± 0.1	2.82 ± 0.11	1.46 ± 0.01	1.27 ± 0.05
AT18-059	392	C2	South	23	236.0 ± 0.1	233.1 ± 0.1	38.1 ± 0.1	2.82 ± 0.11	1.41 ± 0.01	1.29 ± 0.05
AT18-061	468	C2	South	20	448.9 ± 0.1	430.0 ± 0.1	106.2 ± 0.1	2.82 ± 0.11	1.58 ± 0.01	1.38 ± 0.05
AT18-062	470	C2	South	20	272.2 ± 0.1	270.3 ± 0.1	77.6 ± 0.1	2.82 ± 0.11	1.51 ± 0.01	1.27 ± 0.05
AT18-063	492	C2	Ridgetop	5	91.3 ± 0.1	89.8 ± 0.1	7.7 ± 0.1	2.82 ± 0.11	1.37 ± 0.02	1.31 ± 0.06
AT18-106	455	C5	Ridgetop	22	233.9 ± 0.1	231.4 ± 0.1	92.3 ± 0.1	2.82 ± 0.11	1.43 ± 0.01	1.08 ± 0.04
AT18-108	447	C5	South	8	116.2 ± 0.1	115.0 ± 0.1	9.8 ± 0.1	2.82 ± 0.11	1.63 ± 0.02	1.57 ± 0.07
AT18-111	436	C5	South	10	369.9 ± 0.1	366.0 ± 0.1	118.0 ± 0.1	2.82 ± 0.11	1.56 ± 0.03	1.29 ± 0.06
AT18-113	415	C5	South	10	228.9 ± 0.1	226.6 ± 0.1	59.9 ± 0.1	2.82 ± 0.11	1.52 ± 0.02	1.30 ± 0.06
AT18-115	395	C5	South	16	161.9 ± 0.1	159.3 ± 0.1	35.5 ± 0.1	2.82 ± 0.11	1.37 ± 0.01	1.19 ± 0.05
AT18-117	358	C5	South	19	345.6 ± 0.1	341.5 ± 0.1	71.2 ± 0.1	2.82 ± 0.11	1.09 ± 0.01	0.94 ± 0.04
AT18-120	319	C5	South	42	405.5 ± 0.1	400.9 ± 0.1	105.9 ± 0.1	2.82 ± 0.11	1.30 ± 0.01	1.09 ± 0.04
AT18-121	321	C5	North	17	474.4 ± 0.1	470.7 ± 0.1	188.3 ± 0.1	2.82 ± 0.11	1.79 ± 0.01	1.43 ± 0.06
AT18-123	348	C5	North	21	231.2 ± 0.1	228.5 ± 0.1	50.1 ± 0.1	2.82 ± 0.11	1.38 ± 0.01	1.20 ± 0.05
AT18-129	405	C5	North	7	137.1 ± 0.1	135.1 ± 0.1	14.9 ± 0.1	2.82 ± 0.11	1.29 ± 0.02	1.21 ± 0.05
AT18-133	429	C5	North	7	239.0 ± 0.1	236.1 ± 0.1	20.4 ± 0.1	2.82 ± 0.11	1.29 ± 0.03	1.23 ± 0.06
AT18-136	478	C5	North	10	164.7 ± 0.1	163.2 ± 0.1	41.3 ± 0.1	2.82 ± 0.11	1.20 ± 0.09	1.00 ± 0.11
AT18-138	524	C5	Ridgetop	4	138.1 ± 0.1	136.4 ± 0.1	16.7 ± 0.1	2.82 ± 0.11	1.38 ± 0.02	1.28 ± 0.06

[a] *DTM-derived.*
[b] *Soil pit depth below the surface as measured in the field.*
[c] *Field-state aliquot mass.*

[d] *Oven-dried aliquot mass.*
[e] *Mass of rocks (> 2 mm) in an aliquot sample.*
[f] *Bedrock density as measured by submerging bedrock and unweathered saprolite samples from catchment C5 under water (n = 28).*
[g] *Dry bulk density. Uncertainties include the 1σ uncertainty in volume as obtained from the tests performed on the artificial pit and the accuracy of the balance used.*
[h] *Dry soil density. Uncertainties include the 1σ uncertainty in volume as obtained from the tests performed on the artificial pit and the accuracy of the balance used.*

S4 Regular freeware workflow as applied in this study

To facilitate the application of density measurements following the workflows presented here, we give a detailed protocol of the freeware computing steps involved below.

<u>Mesh generation using Regard3D (ver. 1.0.0)</u>

1) Upload the pictures (*Add Picture Set* → *Add files*). Create two picture sets per model, one set containing photographs from the pre-dug surface and one set containing the pictures taken from the excavated pit. Name the picture sets accordingly.
2) *Compute matches*. If needed, *Image correlations parameters* can be adjusted. We found that increasing the *keypoint sensitivity* can improve the final mesh significantly. Regularly, all default parameters can be used.
3) Create the sparse cloud (*Triangulation*). If the *Triangulation* is not successful, the *Triangulation parameters* can be changed to *Old incremental Structure from Motion*, where an initial image pair has to be selected. Regularly, all default parameters can be used.
4) Densify the point cloud (*Create dense pointcloud*). If image contrasts are high and the photographs generally bright and colourful, as it should be the case for the majority of photographs taken in the field, all default parameters can be used. In some cases, we changed the *Minimum image number* to *2*. If this does not work, the *Densification method* can be changed to *Multi-View Environment (MVE)*. Further improvements using this method can be achieved by decreasing the *Scale* and increasing the *Filter width* at the expense of additional computing time. For the reconstruction of the artificial pit we used for testing purposes, we often applied a *Scale* of *3* and a *Filter width* of *5*.
5) Create the mesh. We used the *Poisson surface reconstruction* to create the surfaces. For the alignment of the pre-dug and pit surfaces it can be useful to create *Textures* that may allow for a more accurate tie point assignment (*Colorization method* → *Textures)*. We found that *Textures* will be most accurately placed on the surfaces if *Photometric outlier removal* under *Texturization parameters* is set to *Gauss damping*, with *Geometric visibility test*, *Global seam levelling*, and *Local seam levelling* are being activated. All other parameters can be left as default.

6) Save the surfaces as OBJ file using *Export surface*. If *Textures* have been created, the surface should be saved into a new folder, separated from other exported surfaces.

Scaling, surface alignment and merging in CloudCompare (ver. 2.11)

7) Import the surfaces (*Open* or *Drag and Drop*).
8) Click on the respective meshes and check the *Visible* box in the *Properties* window, uncheck the *Normals* box. Now the textured meshes should be displayed.
9) It might be necessary to roughly clip the reconstructed pit in order to facilitate further processing. In the *Main tools* toolbar, chose the *Segment* tool. Cut out the pit.
10) Zoom on a scale within a scene (i.e. a scale bar or an object with known measures). In the *Main tools* toolbar, chose the *Point picking* tool. Use the *Select 2 points and display segment information* function of the tool to trace the length of the scale. Place two points on the scale with a known distance from each other (e.g. on the 1-cm-mark and on the 4-cm-mark of a folding rule), as visible from the model's texture.
11) Divide the measured distance by the true distance to obtain the scaling factor (e.g. the true length between the 1-cm-mark and 4-cm-mark is 3.00 cm, and the distance measured is 1.15 length units (lu), then the scaling factor would be 3.00 cm / 1.15 lu = 2.61 cm lu^{-1}).
12) Navigate to *Edit* → *Multiply/Scale* and insert the scaling factor. Make sure that the options *Same scale for all dimensions* and *Rescale Global shift* are both checked.
13) The scaling of the pit mesh might have caused a large contrast in size between pit and pre-dug surface meshes. A rough scaling can thus also be applied to the pre-dug surface mesh in order to facilitate the alignment procedure. Alternatively, the mesh can be automatically scaled using the *Match scales* tool (*Tools* → *Registration*).
14) If necessary, roughly clip the pre-dug surface mesh (see #9).
15) In the *DB Tree*, select both the pre-dug surface and the pit mesh. In the *Main tools* toolbar, select *Align (point pairs picking)*. Chose the scaled pit mesh as *Reference*.
16) Mark four or more point pairs in both meshes to align the models. By clicking on *align*, a preview of the alignment, including a display of alignment errors, can be obtained. The final alignment can be approved by clicking on the green tick.
17) Clip the aligned meshes to their outer rims, i.e. to the extent where the pre-dug surface has been modified by digging. To facilitate this working step, the meshes can be colourised in different colours to enhance surface contrasts (*Edit* → *Colors* → *Set unique*). Textures can be hidden by removing the tick at *Materials/textures* in *Mesh* (Mesh *Properties*). Alternatively, clipping can be executed after step #18.

18) Merge the two meshes by using the *Merge multiple clouds* tool (*Main tools* toolbar). Make sure that both meshes are selected. A new *Merged mesh* will appear in the *DB Tree*.
19) Export the merged mesh by selecting it in the *DB Tree* and clicking on *Save* in the *Main tools* toolbar. In this work, the files were saved as PLY for convenience.

<u>Building the watertight mesh using Microsoft 3D Builder (ver. 18.0.1931.0)</u>

20) Import the mesh in Microsoft 3D Builder (*Load object* or *Drag and Drop*).
21) Chose the *File's units* and import the model (*Import model*). A window should appear with a message notifying the user that *One or more objects are invalidly defined. Click here to repair.* Click on the message, and the program will automatically bridge the voids between the two surfaces.
22) Export the watertight mesh (*Menu* → *Save as*). The volume can now be obtained from various programs, e.g. CloudCompare or Meshlab (ver. 2016.12).
23) In those cases where the two surfaces did not sufficiently overlap after merging, the bridging as implemented in the Microsoft 3D Builder might fail (creating two single watertight meshes instead of one). To resolve this problem, the bridging must be performed manually by establishing a connection between the two meshes. We used netfabb Basic (ver. 7.4.0) to achieve this. The merged mesh can be imported into the program (*Project* → *Add Part* or *Drag and Drop*). Under *Extras*, chose *Repair part*. Zoom to the outer rim of the merged mesh, where the two surfaces should be about to converge. Use the *Add Triangles* tool (*Mesh Edit)* and click on the outer edge of the pre-dug surface; then click on the closest outer edge of the pit surface. After the bridge has been created, execute *Apply Repair*. In the *Context Area*, the modified mesh can be exported by right-clicking on the mesh and choosing *Export Part*. Once this step is performed, continue with step #20.