

Supplementary Online Materials

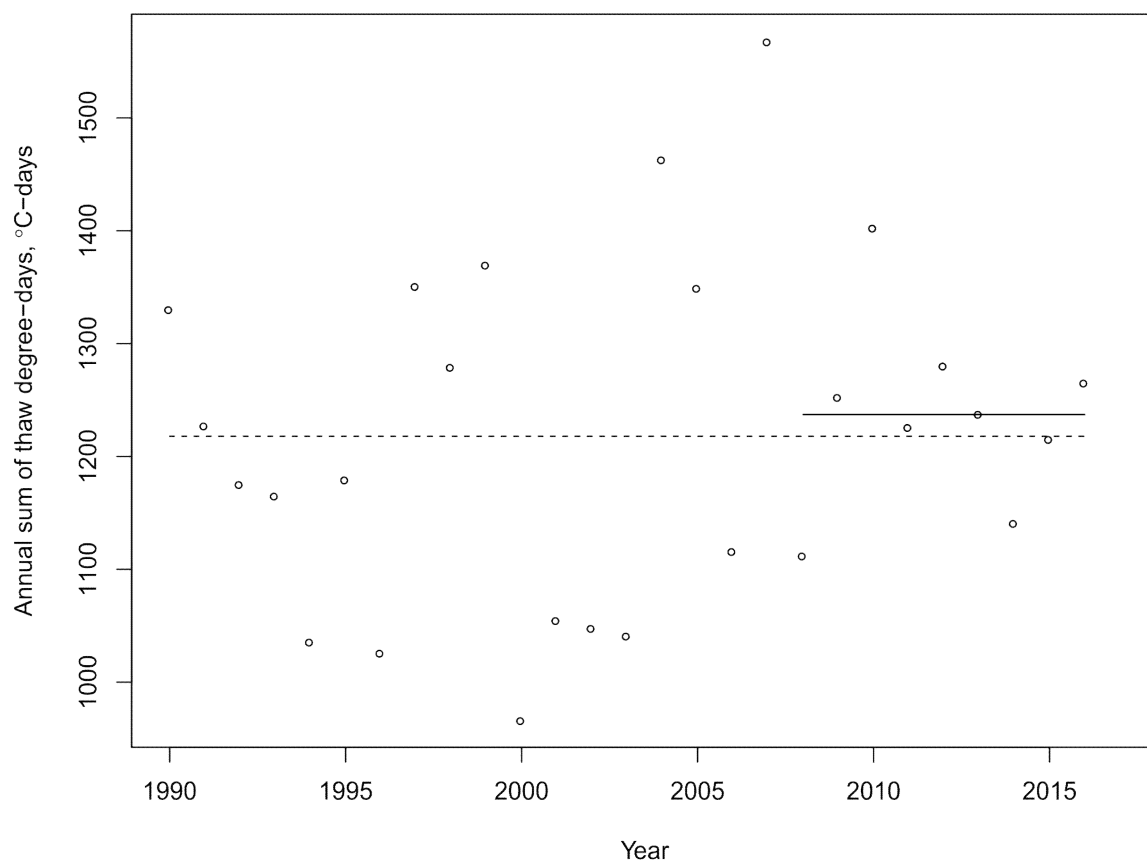


Figure S1. Annual sum of thaw degree-days (TDDs) at Noatak RAWS, 1990-2016. The mean was 1218°C-day (dashed line) and standard deviation was 146°C-day. The mean for the period of most of our slump monitoring (2008-2016) was 1237°C-day (solid horizontal line). Trends were non-significant by linear regression and Mann-Kendall test for both time intervals (see text).

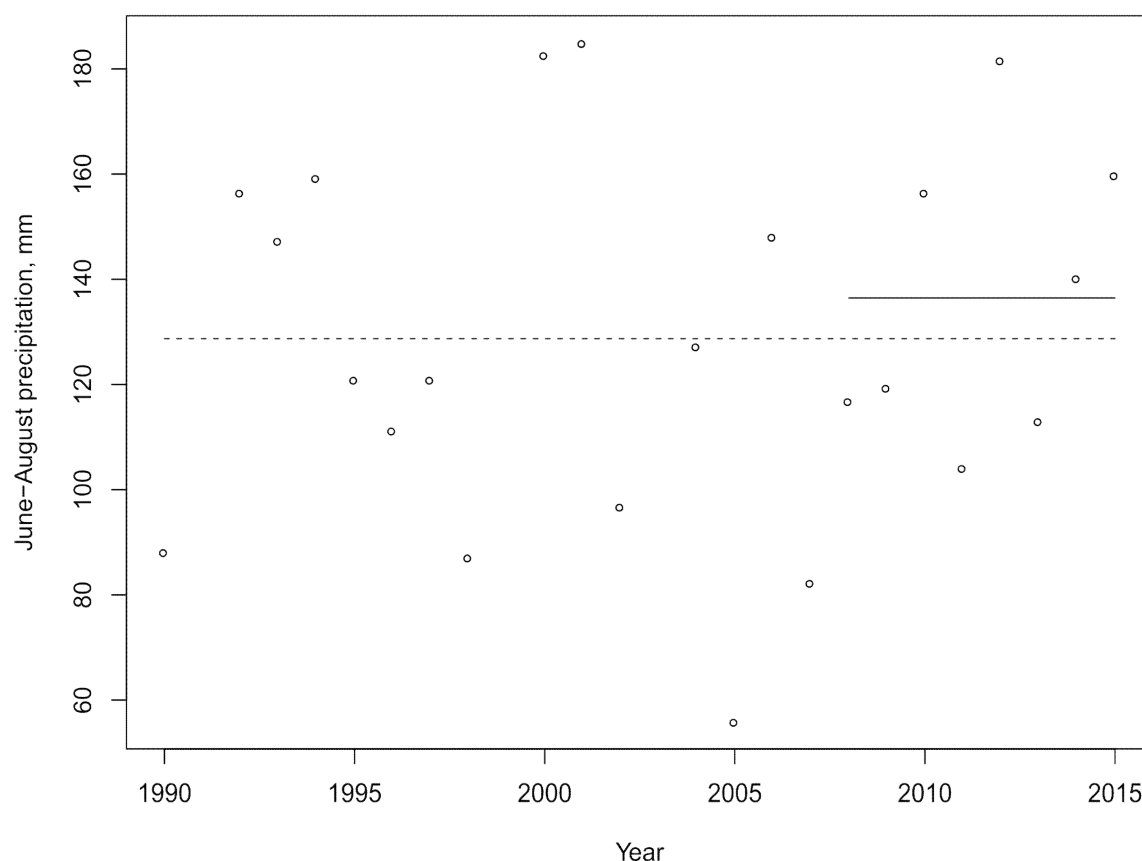


Figure S2. Sum of June-August precipitation at the Noatak RAWS, 1990-2015. Data are missing for 1991, 1999, 2003, and 2016. The mean for 1990-2015 was 129 mm (dashed line) and standard deviation was 35 mm. The mean for the period of most of our slump monitoring (2008-2016) was 136 mm (solid horizontal line). Trends were non-significant by linear regression and Mann-Kendall test for both time intervals (see text).

Table S1. Slump locations and sample events

Slump	Location		Sample Years ¹										Count
	Longitude	Latitude	2006	2007	2008	2010	2011	2012	2013	2014	2016		
GAAR0008	-156.4862	67.9007			s	o	o	o		vg		5	
NOAT0039	-159.2914	68.0359	v	s		o	v	o			vg	6	
NOAT0042	-159.2346	68.0239	v	s		o	v	o			vg	6	
NOAT0068	-156.7884	67.9610			s	o	o	o	vg	vg	vg	7	
NOAT0069	-156.7927	67.9606			s	o	o	o	vg	vg	vg	7	
NOAT0070	-156.8260	67.9588			s	o	o	o	vg	vg	vg	7	
NOAT0071	-156.8003	67.9426			s	o		o	vg	vg		5	
NOAT0072	-156.8066	67.9437			s	o		o	vg	vg		5	
NOAT0073	-156.8189	67.9476			s	o		o	vg	vg		5	
NOAT0074	-156.6004	67.8978			s	o	v	o	vg			5	
NOAT0076	-156.6044	67.8943			s	o	v	o	vg			5	
NOAT0148	-157.5324	67.8768			s	o	o	o	vg	vg	vg	7	
NOAT0151	-157.5267	67.8629			s	o	o	o	vg	vg	vg	7	
NOAT0159	-156.7358	67.8830			s	o	o	o	vg			5	
NOAT0160	-156.7353	67.8811			s	o	o	o	vg			5	
NOAT0161	-156.5468	67.8933			s	o	o	o	vg			5	
NOAT0172	-156.6816	67.8064			s	o	o	o				4	
NOAT0237	-157.9354	67.7049			s	o	o	o		vg		5	

NOAT0238	-157.9360	67.7041	s	o	o	o	vg	5
NOAT0247	-157.8517	67.6697	s	o	o		vg	4
NOAT0248	-157.8529	67.6707	s	o	o		vg	4
NOAT0265	-161.0918	67.9475	v		o	o	vg	4

¹Sampling codes are as follows: o – oblique aerial photographs, s – satellite imagery, v – vertical aerial photographs, vg – vertical aerial photographs with accurate camera locations from aerial GPS

Table S2. Slump climate and elevation data¹

Slump	Elevation, m	FDD	TDD	MAAT	MDGT 1950	MDGT 2000	MDGT 2050	MDGT 2090	ALT 1950	ALT 2000	ALT 2050	ALT 2090
GAAR0008	612	4165	909	-9.0	-6.5	-5.4	-3.8	-1.7	0.43	0.42	0.45	0.52
NOAT0039	327	4106	1094	-8.4	-8.2	-6.5	-4.7	-2.4	0.67	0.76	0.88	1.09
NOAT0042	323	4122	1078	-8.4	-6.7	-5.4	-3.9	-2.2	0.53	0.56	0.61	0.68
NOAT0068	598	4367	835	-9.8	-8.4	-7.3	-5.6	-3.3	0.65	0.65	0.76	0.96
NOAT0069	600	4328	846	-9.6	-8.5	-7.2	-5.5	-3.2	0.64	0.65	0.77	0.96
NOAT0070	561	4237	893	-9.3	-8.5	-6.9	-5.2	-2.9	0.64	0.69	0.79	1.00
NOAT0071	546	4197	921	-9.1	-6.8	-5.5	-4.2	-2.4	0.52	0.53	0.57	0.65
NOAT0072	536	4198	921	-9.1	-8.3	-6.8	-5.0	-2.8	0.65	0.70	0.81	1.02
NOAT0073	527	4234	902	-9.2	-6.8	-5.4	-4.0	-2.0	0.54	0.55	0.61	0.70
NOAT0074	563	4077	982	-8.6	-6.4	-5.2	-3.9	-2.3	0.42	0.43	0.45	0.49
NOAT0076	564	4077	982	-8.6	-6.7	-5.2	-3.7	-1.7	0.77	0.85	0.93	1.14
NOAT0148	452	3983	1002	-8.3	-6.5	-5.0	-3.4	-1.3	0.77	0.86	0.96	1.18
NOAT0151	462	3923	1013	-8.1	-6.3	-4.7	-3.1	-0.9	0.42	0.45	0.48	0.55
NOAT0161	556	4081	980	-8.6	-6.5	-5.2	-3.9	-2.2	0.52	0.55	0.57	0.65
NOAT0159	515	4079	999	-8.5	-6.6	-5.1	-3.6	-1.6	0.78	0.87	0.95	1.16
NOAT0160	529	4079	999	-8.5	-7.1	-5.5	-3.9	-1.6	0.44	0.47	0.50	0.58
NOAT0172	646	3784	971	-7.8	-5.9	-4.4	-2.8	-0.7	0.42	0.44	0.47	0.54
NOAT0237	421	3692	1128	-7.1	-5.5	-3.9	-2.3	-0.1	0.44	0.48	0.50	0.58
NOAT0238	412	3692	1128	-7.1	-5.5	-3.9	-2.3	-0.1	0.44	0.48	0.50	0.58
NOAT0247	454	3658	1143	-7.0	-6.1	-4.5	-2.9	-0.8	0.43	0.46	0.50	0.57
NOAT0248	444	3658	1143	-7.0	-5.4	-3.8	-2.2	0.0	0.45	0.48	0.51	0.58
NOAT0265	158	3974	1106	-8.0	-7.3	-5.5	-3.6	-1.4	0.42	0.47	0.51	0.59
Noatak	340	4163	1078	-8.6	-6.8	-4.2	-3.5	-1.3	0.43	0.46	0.50	0.57
RAWS												

¹FDD – freezing degree-days in °C-days; TDD – thaw degree-days in °C-days; MAAT – mean annual air temperature in °C; from modeled raster data for the period 1970–2000 by PRISM Climate Group (2009); MDGT – mean decadal ground temperature in °C; ALT – active layer thickness in m; from modeled raster data by Panda et al. (2016). The year (1950, 2000, etc.) indicates the start year for a modeled decadal average.

Estimation of missing values from Noatak RAWS

Missing data during the thaw season (May–Sept) at the Noatak RAWS affected a few years (Table S3). Most of these gaps were filled by estimates from the next nearest weather station with data for our period of observations, the Kelly RAWS (Applied Climate Information System 2017, Fig. 1). Linear regression of the Noatak and Kelly RAWS mean daily temperatures for the thaw season (May–Sep) and the available period of record (1990–2016) yielded an r-squared of 0.873 and regression formula of $y = 1.021198x - 1.608490$, where y is the Noatak mean daily temperature and x is the Kelly mean temperature; $n = 3413$. Most of the days missing data from both stations were from May 1994 and 1995, during timespans of the year when less than 5% of the annual thaw degree-days (TDD) typically accumulate. Total TDD for these two years were estimated using long-term average values for the missing dates. Data for 5 other scattered missing dates were interpolated from adjacent days with data.

Table S3. Days of missing temperature data from the Noatak RAWs, May-Sep, 1990-2016

Year	Month				
	May	Jun	Jul	Aug	Sep
1990	0	0	0	0	0
1991	31	30	31	31	12
1992	0	0	0	0	0
1993	0	0	2	0	0
1994	31	4	0	0	0
1995	17	0	0	0	0
1996	0	0	0	0	0
1997	0	0	0	0	2
1998	0	0	0	0	0
1999	0	0	0	0	0
2000	17	0	0	0	0
2001	0	0	0	0	0
2002	14	0	0	0	0
2003	31	29	0	0	0
2004	31	8	1	0	0
2005	0	0	0	0	0
2006	0	0	0	0	2
2007	0	0	0	0	0
2008	0	0	0	0	0
2009	0	0	0	0	0
2010	0	0	0	0	0
2011	0	0	0	0	0
2012	0	0	0	0	0
2013	0	0	0	0	0
2014	0	0	0	0	0
2015	0	0	0	0	0
2016	20	30	31	11	0

Table S4. Missing data from both the Noatak and Kelly RAWs, May-Sep 1990-2016

Year	Month				
	May	Jun	Jul	Aug	Sep
1990	0	0	0	0	0
1991	1	0	1	0	0
1992	0	0	0	0	0
1993	0	0	0	0	0
1994	31	3	0	0	0
1995	17	0	0	0	0
1996	0	0	0	0	0
1997	0	0	0	0	2
1998	0	0	0	0	0
1999	0	0	0	0	0
2000	0	0	0	0	0
2001	0	0	0	0	0
2002	0	0	0	0	0
2003	0	0	0	0	0
2004	0	0	1	0	0
2005	0	0	0	0	0

2006	0	0	0	0	0
2007	0	0	0	0	0
2008	0	0	0	0	0
2009	0	0	0	0	0
2010	0	0	0	0	0
2011	0	0	0	0	0
2012	0	0	0	0	0
2013	0	0	0	0	0
2014	0	0	0	0	0
2015	0	0	0	0	0
2016	0	0	0	0	0

Table S5. Summary of differences between dimensions measured on georeferenced models and by a total station on the ground¹

Slump	Year of Ground Survey	Year of Aerial Georeferenced Model	Mean of % Error in horizontal distance	Std Dev of % Error in distance	Mean of % Error in elevation change	Std Dev of % Error in elevation change	N
GAAR008 ²	2011	2014	2.62	0.37	-2.06	4.67	5
GAAR008gnd ²	2011	none	-0.25	0.31	-0.11	0.13	5
NOAT039	2010	2016	-0.13	0.26	-0.02	0.17	5
NOAT068	2010	2013	-0.70	1.01	-0.39	0.15	5
NOAT070	2010	2013	0.05	1.19	-0.08	0.05	5
NOAT071	2010	2013	-0.93	1.6	0.09	0.42	5
NOAT074	2011	2013	0.02	0.14	-0.04	0.08	5
NOAT076	2011	2013	0.05	0.75	-0.12	0.08	5
NOAT148	2010	2013	0.61	0.17	0.53	0.40	5
NOAT151	2011	2013	-0.08	0.08	0.04	0.08	10
NOAT159,160	2011	2013	-0.12	0.36	0.03	0.17	11
NOAT161	2010	2013	0.77	1.05	0.42	0.81	5
NOAT172 ³	2010	none	0.05	0.07	0.01	0.04	5
NOAT237,238	2011	2014	-0.19	0.85	-0.01	0.17	7
NOAT247,248	2010	2013	-0.04	0.12	0.00	0.02	5
NOAT265	2011	2016	0.05	0.45	-0.06	0.12	7
ALL ³	2010-11	2013-16	-0.12	0.87	0.04	0.34	80

¹Distances and elevation changes between a single total station setup and multiple prism-pole target points measured on the ground using a total station, compared to measurements made on a 3D model (orthophotograph and DEM) that was registered using landmarks to a model georeferenced by aerial GPS from the year indicated. The differences between the two measurements were divided by the length of the total station shot and multiplied by 100 to obtain the percent error (i.e. the error in meters expected for a 100 m measurement). Negative signs indicate distances and elevations on the model were less than the survey measurements.

²The only available aerially georeferenced model for GAAR008 (2014) produced a relatively inaccurate basemap for georeferencing other years of data (see text for explanation). The models for this slump were re-georeferenced using the 2011 ground survey points, and these were used in further analysis. The accuracy statistics presented under “GAAR008gnd” depict the difference between the 2011 model and the points used to georeference it.

³The overall accuracy was computed without the data for slump GAAR008 (see footnote 2) and NOAT172. These were omitted because they were georeferenced using the ground survey points, not the aerial GPS, and

thus the accuracy statistics represent only an internal check on the ability of the model to reproduce the coordinates used to georeferenced it.

Table S6. Regression Coefficients for Curves of Slump Area Growth vs. Cumulative Thaw Degree-Days¹

Slump	a	b	c	r ²	n
GAAR008	-9.80E-05	2.71	-4756.99	0.996	5
NOAT039	-2.14E-04	6.24	5490.35	0.999	6
NOAT042	-8.66E-05	2.57	916.12	0.998	5
NOAT068	-4.64E-05	4.50	-8355.45	0.999	6
NOAT069	-4.35E-05	3.02	-10521.40	0.994	7
NOAT070	-2.11E-04	9.20	-24736.16	0.996	7
NOAT071	3.93E-08	0.09	8108.29	0.998	5
NOAT072	-4.44E-05	1.24	-1178.24	0.998	5
NOAT073	-2.97E-05	0.83	755.90	0.998	5
NOAT074	-1.87E-04	5.31	-21325.68	0.994	5
NOAT076	-1.32E-04	3.43	-8964.40	1.000	5
NOAT148	-6.67E-05	2.84	-1943.77	0.997	7
NOAT151	-1.32E-04	5.62	6315.91	0.997	7
NOAT159	-1.28E-04	3.02	-10009.84	0.991	5
NOAT160	-1.00E-04	2.45	-4514.85	0.993	5
NOAT161	-1.60E-04	4.07	-9262.74	1.000	5
NOAT172	-5.59E-05	1.96	-1812.22	0.997	4
NOAT237	-1.99E-05	2.31	-8395.66	0.987	5
NOAT238	-3.95E-05	1.04	-973.26	0.985	5
NOAT247	-4.42E-06	0.22	7186.16	0.982	4
NOAT248	-1.76E-05	0.52	6154.03	1.000	4
NOAT265	-1.88E-04	6.68	-16232.03	1.000	4

¹Coefficients are for quadratic equations of the form $y = ax^2 + bx + c$, where x is the sum of degree-days (°C-days) accumulated since 1 Jan 2004 and y is the area in square meters; r^2 is the correlation coefficient and n the sample size.

Table S7. Regression Coefficients for Curves of Slump Centerline Scarp Position vs. Cumulative Thaw Degree-Days¹

Slump	a	b	c	r ²	n
GAAR008	-1.345E-06	0.0346	-33.79	0.999	5
NOAT039	-3.640E-07	0.0119	118.40	0.991	6
NOAT042	-3.944E-07	0.0130	42.98	0.996	5
NOAT068	-8.323E-08	0.0212	40.33	0.996	6
NOAT069	-7.431E-07	0.0397	-33.59	0.996	7
NOAT070	-4.871E-07	0.0323	-11.74	0.995	7
NOAT071	-9.451E-08	0.0038	149.04	0.998	5
NOAT072	-8.029E-07	0.0201	24.53	0.990	5
NOAT073	-5.453E-07	0.0153	14.19	0.996	5
NOAT074	-1.226E-06	0.0375	-107.38	0.982	5
NOAT076	-1.179E-06	0.0345	-93.50	0.998	5
NOAT148	-3.404E-07	0.0139	46.89	0.998	7
NOAT151	1.037E-08	0.0116	144.42	0.998	7
NOAT159	-1.231E-06	0.0306	-70.91	0.990	5
NOAT160	-1.142E-06	0.0272	-25.25	0.990	5
NOAT161	-1.120E-06	0.0328	-57.92	0.989	5
NOAT172	-1.671E-07	0.0085	124.59	1.000	4

NOAT237	-9.085E-07	0.0337	-52.26	0.993	5
NOAT238	-1.123E-06	0.0288	-45.69	0.971	5
NOAT247	-2.178E-07	0.0057	96.53	0.999	4
NOAT248	-2.341E-07	0.0070	84.05	0.998	4
NOAT265	-1.301E-07	0.0152	64.99	0.996	4

¹Coefficients are for quadratic equations of the form $y = ax^2 + bx + c$, where x is the sum of degree-days (°C-days) accumulated since 1 Jan 2004 and y is the distance along a slump centerline; r^2 the correlation coefficient squared and n is the sample size

Table S8. Regressions Coefficients for Topographic Slope¹

Slump	a	b	c	r ²	n
GAAR008	-3.314E-04	0.1948	593.34	0.992	14
NOAT039	3.202E-16	0.0000	349.00	0.469	6
NOAT042	-4.097E-04	0.1145	338.01	0.998	4
NOAT068	-1.167E-04	0.1616	589.78	0.999	23
NOAT069	-1.122E-04	0.1539	584.53	0.999	25
NOAT070	-1.834E-04	0.1736	564.07	0.998	22
NOAT071	6.756E-04	-0.1911	575.41	0.938	13
NOAT072	-9.571E-04	0.3158	532.00	0.999	11
NOAT073	-3.608E-04	0.1318	542.52	0.999	7
NOAT074	-2.500E-04	0.1255	569.98	0.997	12
NOAT076	-1.705E-04	0.1030	565.79	0.983	10
NOAT148	-2.990E-04	0.1849	441.17	0.998	14
NOAT151	-2.813E-04	0.2232	437.04	0.986	9
NOAT159	-6.626E-04	0.2032	517.67	0.997	9
NOAT160	-8.122E-04	0.2007	523.95	0.998	5
NOAT161	-1.773E-04	0.1458	570.11	0.998	14
NOAT172	-4.906E-04	0.3393	615.01	0.999	9
NOAT237	-3.473E-04	0.1899	417.13	0.995	12
NOAT238	-1.378E-03	0.4234	403.53	0.987	7
NOAT247	-1.672E-03	0.4564	433.38	0.999	9
NOAT248	0.000E+00	0.0000	459.00	--	4
NOAT265	-5.429E-04	0.4344	115.82	0.998	33

¹Coefficients are for quadratic equations of the form $y = ax^2 + bx + c$, where x is the horizontal distance in meters (along the slump centerline), and y is the elevation above sea level; r^2 the correlation coefficient squared and n the sample size.

Table S9. Linear model of slump growth rate (in m per TDD) vs. topographic slope¹

Slump	Regression slope of growth rate in mm per TDD vs. topographic slope (times 10 ³)	Standard error of regression slope (times 10 ³)	P
Intercept	4.31	1.20	0.001
GAAR008	0.35	0.27	0.202
NOAT039	NA	NA	NA
NOAT042	2.04	5.20	0.695
NOAT068	1.36	0.25	0.000
NOAT069	1.94	0.26	0.000
NOAT070	2.19	0.33	0.000
NOAT071	-0.53	1.07	0.621
NOAT072	0.09	0.53	0.866
NOAT073	0.09	0.59	0.883
NOAT074	1.50	0.51	0.004

NOAT076	1.34	0.47	0.005
NOAT148	0.19	0.25	0.453
NOAT151	1.23	0.40	0.003
NOAT159	0.54	0.42	0.204
NOAT160	NA	NA	NA
NOAT161	0.58	0.31	0.068
NOAT172	0.07	0.21	0.733
NOAT237	1.72	0.45	0.000
NOAT238	-0.44	0.54	0.416
NOAT247	NA	NA	NA
NOAT248	NA	NA	NA
NOAT265	0.49	0.21	0.021

¹Overall r-squared 0.68, F-statistic 7.204 on 18 and 62 DF, *p*-value 0.000



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