Supplementary Information for

Isotopic evidence for the impact of artificial snow on the nitrogen cycle in temperate regions

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Appendix A: Geological features

Yongpyong Ski Resort is located in Daegwallyeong, Pyeongchang (Figure 1a). In the Pyeongchang area, the Carboniferous-Triassic Pyeongan Supergroup, which is unconformably underlain by Ordovician Jeongseon limestone, is widely distributed. The sedimentary sequences of the group are subdivided into the Manhang, Guemcheon, Jangseong, Okgapsan, Sangwonsa, and Bakjisan formations in ascending order and are mainly composed of thick sandstones with thinly intercalated shale, coal and limestone in the lower part. The Jurassic granite, which intrudes into the Jeongseon limestone and Pyeongan Supergroup, occurs as coarse-grained, equigranular biotite granite and porphyritic biotite granite with alkali feldspar phenocrysts.

Table S1

Statistics of field parameters and ion concentrations.

Sample (n)		pH	EC[a] (μS/cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Si (mg/L)	Sr (mg/L)	HCO_3[b] (mg/L)	F (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	SO_4 (mg/L)
Stream water (n = 5)	Min	7.2	113.9	11.83	1.97	3.75	0.77	2.78	0.07	20.74	0.00	8.17	2.62	8.29
	Max	7.6	514.9	45.56	6.28	29.83	3.42	5.23	0.32	62.97	0.10	92.50	5.71	14.74
	Mean	7.4	219.6	20.45	3.16	9.11	1.88	3.47	0.13	35.59	0.04	24.15	3.95	11.32
	SD[c]	0.1	166.5	12.75	1.64	10.18	0.97	0.92	0.10	14.87	0.05	33.57	1.38	2.45
Mountain groundwater (W, n = 12)	Min	7.8	97.9	10.12	0.86	0.93	0.08	1.57	0.05	14.63	0.00	4.06	2.61	3.12
	Max	9.3	149.8	16.36	1.61	2.08	0.36	2.36	0.08	26.36	0.16	9.44	4.64	12.62
	Mean	8.7	114.0	13.87	1.24	1.61	0.24	2.07	0.06	21.22	0.02	7.36	3.99	5.50
	SD	0.5	14.9	1.59	0.26	0.28	0.09	0.23	0.01	3.06	0.05	1.50	0.67	2.36
Groundwater (YP, n = 32)	Min	6.1	97.9	8.99	2.21	5.14	0.78	2.99	0.11	33.49	0.00	3.01	0.00	3.53
	Max	9.0	976.0	112.50	17.47	52.31	2.05	9.38	4.67	165.23	0.98	203.28	9.36	51.91
	Mean	7.0	477.4	54.08	7.84	14.78	1.50	6.70	0.64	85.40	0.16	75.63	3.17	16.61
	SD	0.6	280.6	33.18	4.53	10.04	0.30	1.97	1.00	38.00	0.25	65.69	2.03	9.93
Artificial snow (n = 2)	Min	9.2	264.9	23.24	5.70	11.55	2.53	5.09	0.16	43.93	0.03	34.27	5.11	14.53
	Max	9.4	275.3	24.85	5.94	12.73	2.58	5.11	0.17	54.18	0.03	38.95	5.43	15.17
	Mean	9.3	270.1	24.04	5.82	12.14	2.55	5.10	0.16	49.06	0.03	36.61	5.27	14.85
	SD	0.1	7.4	1.14	0.17	0.83	0.04	0.01	0.01	7.25	0.00	3.31	0.23	0.45
Natural snow (n = 5)	Min	5.4	7.1	0.00	0.00	0.47	0.15	0.00	0.00	0.41	0.00	0.16	0.05	0.00
	Max	8.1	129.2	3.51	0.33	1.87	0.35	0.00	0.00	6.96	0.06	3.83	1.31	3.99
	Mean	6.5	54.0	1.72	0.19	0.98	0.25	0.00	0.00	3.85	0.02	1.98	0.67	1.99
	SD	1.0	47.3	1.57	0.18	0.58	0.10	0.00	0.00	2.78	0.03	1.59	0.58	1.77
Rainwater (n = 6)	Min	3.8	23.6	0.54	0.00	0.38	0.12	0.00	0.00	0.00	0.00	0.76	0.00	0.46
	Max	6.9	174.8	14.21	2.32	13.04	8.65	1.06	0.07	29.78	0.60	15.46	5.99	12.91
	Mean	5.9	114.9	5.13	0.71	3.98	2.03	0.20	0.02	12.69	0.20	5.48	1.68	5.03
	SD	1.5	66.1	6.37	0.95	5.44	3.31	0.42	0.03	13.38	0.26	6.61	2.47	5.93

[a]EC: Electrical conductivity

[b]HCO_3 ≈ Total alkalinity

[c]SD: Standard deviation

Table S2

Information relating to snow samples and *in-situ* measurements.

Sample	Code	Date	Depth (cm)	Density (kg/m^3)	Liquid water content (%)
Artificial snow[a]	AS-L1	2021-02-04	60	800	10.6
	AS-L2	2021-02-04	90	847	11.6
Natural snow[b]	NS1-L1	2021-02-04	5	70	5.7
	NS1-L2	2021-02-04	15	117	7.4
	NS1-L3	2021-02-04	25	146	8.2
	NS1-L4	2021-02-04	35	258	7.7
	NS2-L1	2021-03-03	0 (surface)	-	-
	NS2-L2	2021-03-03	20	346	4.3
	NS2-L3	2021-03-03	65	908	10.7

[a]Artificial snow: 100-cm snowpit

[b]Natural snow: 50-cm (2021-02-04) and 85-cm (2021-03-03) snowpit

Table S3

Isotopic compositions of samples collected from September 2020 to August 2022.

Sample	Code	Date	$\delta^{18}O–H_2O$ (‰)	$\delta^{2}H–H_2O$ (‰)	$NO_3^-–N$ (mg/L)	$^{15}N–NO_3$ (‰)	$^{18}O–NO_3$ (‰)
Stream water	SW-1	2020-09-25	−9.32	−61.35	3.16	7.99	0.54
	SW-2	2021-02-04	−10.01	−66.95	5.71	12.84	3.43
	SW-3	2021-05-21	−9.62	−63.53	2.62	8.30	1.04
	SW-4	2021-11-10	−10.04	−67.32	5.66	9.94	0.60
	SW-5	2022-08-02	−9.81	−65.42	3.62	9.72	2.40
Groundwater (W1)	W1-1	2020-09-25	−10.56	−70.00	4.29	7.08	2.05
	W1-2	2020-11-03	−10.58	−70.01	4.60	6.51	1.60
	W1-3	2021-02-04	−10.67	−70.72	4.43	7.05	2.50
	W1-4	2021-05-21	−10.60	−70.12	4.40	7.29	−1.69
	W1-5	2021-11-10	−10.53	−69.58	3.09	6.45	2.04
	W1-6	2022-08-02	−10.56	−70.33	4.13	6.82	3.15
Mountain groundwater (W2)	W2-1	2020-09-25	−10.67	−70.91	3.91	7.22	2.30
	W2-2	2020-11-03	−10.73	−71.32	3.16	6.81	1.68
	W2-3	2021-02-04	−10.76	−71.65	4.55	6.61	2.92
	W2-4	2021-05-21	−10.74	−71.08	4.64	7.77	1.10
	W2-5	2021-11-10	−10.69	−71.05	2.62	6.92	8.47
	W2-6	2022-08-02	−10.72	−71.27	4.03	6.83	2.73
Artificial snow	AS-L1	2021-02-04	−8.95	−62.28	5.11	9.88	3.39
	AS-L2	2021-02-04	−9.20	−64.32	5.43	10.69	1.89
Natural snow	NS1-L3	2021-02-04	-	-	0.98	6.31	77.80
	NS1-L4	2021-02-04	−13.94	−81.29	1.30	5.53	76.28
	NS2-L1	2021-03-03	−12.69	−88.75	0.05	-	-
	NS2-L2	2021-03-03	−12.75	−89.23	0.06	-	-
	NS2-L3	2021-03-03	−11.46	−63.51	0.96	-	-
Rainwater (High altitude)	RW-H1	2021-02-04	-	-	3.36	8.34	66.80
	RW-H2	2021-05-21	−13.97	−96.70	ND[a]	-	-
	RW-H3	2022-08-02	−11.72	−81.58	0.44	2.12	17.87
Rainwater (Low altitude)	RW-L1	2021-02-04	-	-	5.99	5.70	86.09
	RW-L2	2021-05-21	−11.48	−77.52	0.24	-	-
	RW-L3	2022-08-02	−10.48	−75.58	0.06	-	-

[a]ND: not detected

Table S4

Typical values of $\delta^{15}N$ and $\delta^{18}O$ of nitrate derived or nitrified from various N sources.

Source	$\delta^{15}N–NO_3$ (‰)	Reference	$\delta^{18}O–NO_3$ (‰)	Reference
Atmospheric depositions	−10 to +15	Kendall, 1998	+25 to +85 ($AgNO_3$ method)	Kendall et al., 2007
NO_3^- fertilizer	−5 to +5	Wassenaar, 1995	+17 to +25	Xue et al., 2009
NH_4^+ in fertilizer and precipitation	−8.0 to +6.2	Hübner, 1986		
Soil NH_4^+	0 to +8	Xue et al., 2009	−15 to +15	Kendall et al., 2007
Sewage	+4 to +19	Xue et al., 2009		
Manure	+5 to +25	Xue et al., 2009		

Table S5

End-member isotopic composition affecting nitrate sources of mountain groundwater.

Source	$\delta^{15}N–NO_3$ (‰)		$\delta^{18}O–H_2O$ (‰)	
	Mean	SD	Mean	SD
Artificial snow (*n* = 2)	10.28	0.57	−9.08	0.17
Natural snow (*n* = 4)	5.92	0.55	−12.71	1.01
Rainwater (*n* = 1)	2.12	-	−11.7	-

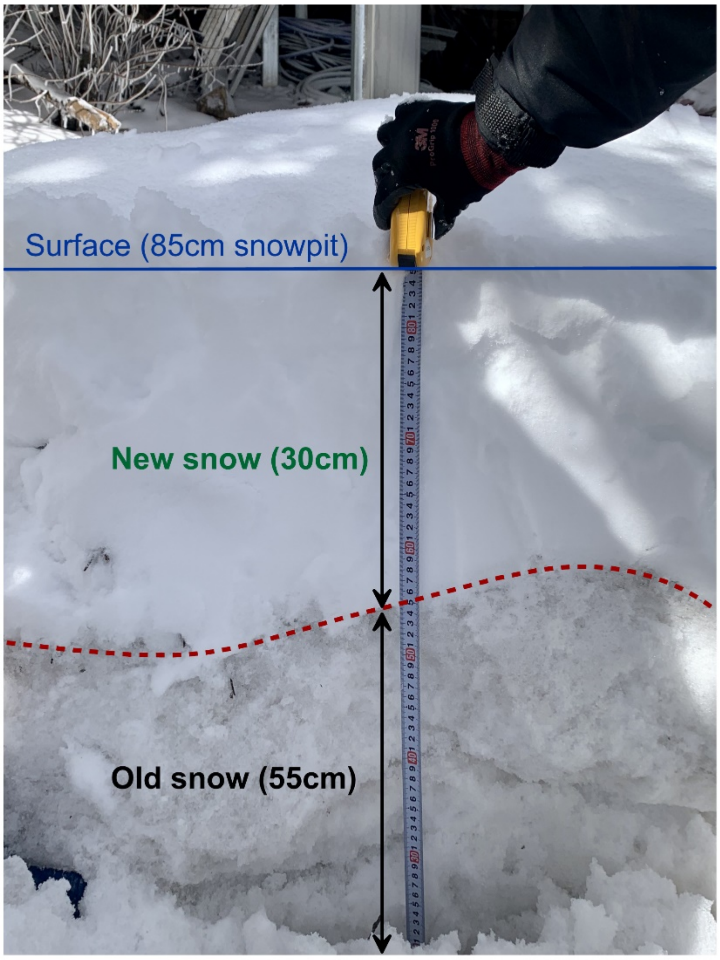

Figure S1. Snowpit dug into the surface of snowpack on the mountain summit in March 2021.

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