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Primary succession and its driving variables – a sphere-spanning approach applied in proglacial areas in the upper Martell Valley (Eastern Italian Alps)

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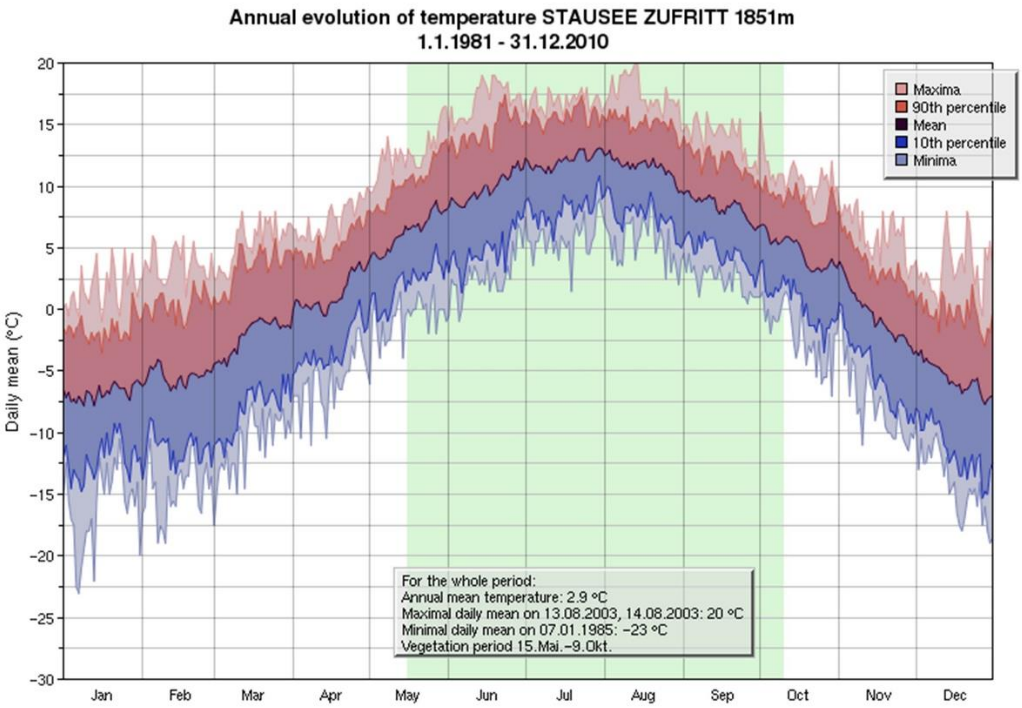
(a)



(b)

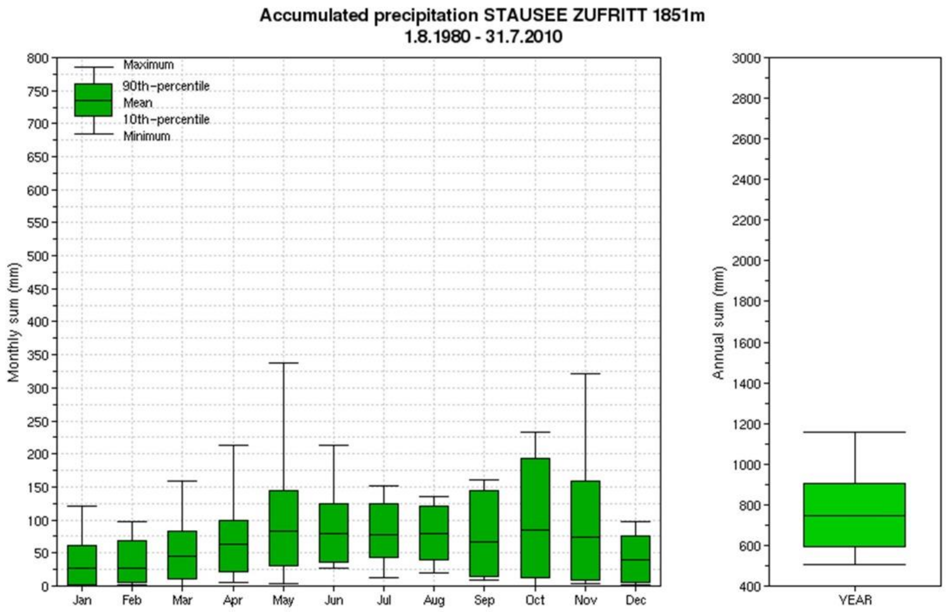


Figure S1: (a) Annual distribution of the temperature with the daily mean temperature [°C] and (b) accumulated precipitation with the monthly and annual sum [mm] at lake Zufritt (1851 m a.s.l.) for the 30-year climate period 1981 to 2010 and 1980 to 2010 respectively (graphs from the 3PCLIM-project; source: www.3pclim.eu; accessed on 29.04.2023).

Table S1: List of the literature review with the author(s), publication year, title, journal, and location of the study.

Author	**Year**	**Title**	**Journal**	**Location**
Haselberger et al.	2021	Quantification of biogeomorphic interactions between small-scale sediment transport and primary vegetation succession on proglacial slopes of the Gepatschferner, Austria	Earth Surface Processes and Landforms	European Alps
Knoflach et al.	2021	Modelling of Vegetation Dynamics from Satellite Time Series to Determine Proglacial Primary Succession in the Course of Global Warming—A Case Study in the Upper Martell Valley (Eastern Italian Alps)	Remote Sensing	European Alps
Losapio et al.	2021	The consequences of glacier retreat are uneven between plant species	frontiers in Ecology and Evolution	European Alps
Wei et al.	2021	Characteristics and controls of vegetation and diversity changes monitored with an unmanned aerial vehicle (UAV) in the foreland of the Urumqi Glacier No. 1, Tianshan, China	Science of the Total Environment	Asia
Wietrzyk-Pełka et al.	2021	Patterns and drivers of cryptogam and vascular plant diversity in glacier forelands	Science of the Total Environment	Scandinavia
Wojcik et al.	2021	How allogenic factors affect succession in glacier forefields	Earth -Science Reviews	
Llambi et al.	2021	Vegetation Assembly, Adaptive Strategies and Positive Interactions During Primary Succession in the Forefield of the Last Venezuelan Glacier	frontiers in Ecology and Evolution	S-America
Bayle	2020	A recent history of deglaciation and vegetation establishment in a contrasted geomorphological context, Glacier Blanc, French Alps	Journal of Maps	European Alps
Fickert	2020	Common patterns and diverging trajectories in primary succession of plants in eastern alpine glacier forelands	diversity	European Alps
Lambert et al.	2020	Vegetation change as related to terrain factors at two glacier forefronts, Glacier National Park, Montana, USA	Journal of Mountain Science	N-America
Eichel	2019	Vegetation succession and biogeomorphic interactions in glacier forelands	Book: Geomorphology of Proglacial Systems	European Alps
Fischer et al.	2019	Vegetation dynamics in Alpine glacier forelands tackled from space	nature/scentific reports	European Alps
Franzén et al.	2019	Rapid plant colonization of the forelands of a vanishing glacier is strongly associated with species traits	Arctic, Antarctic, and Alpine Research	Scandinavia
Szymański et al.	2019	Impact of parent material, vegetation cover, and site wetness on variability of soil properties in proglacial areas of small glaciers along the northeastern coast of Sørkappland (SE Spitsbergen)	Catena	Scandinavia
Fickert & Grüninger	2018	High-speed colonization of bare ground—Permanent plot studies on primary succession of plants in recently deglaciated glacier forelands	Land Degradation & Development	European Alps
Wietrzyk et al.	2018	The relationships between soil chemical properties and vegetation succession in the aspect of changes of distance from the glacier forehead and time elapsed after glacier retreat in the Irenebreen foreland (NW Svalbard)	Plant soil	Scandinavia

Author	Year	Title	Journal	Location
Shahid & Mirza	2019	An Analysis of Glacial Retreat and Resultant Vegetation Expansion in the Karakorum: A case study of Passu Glacier in Hunza valley	Biologia (Pakistan)	Asia
Cazzolla et al.	2018	The last 50 years of climate-induced melting of Maliy Aktru glacier (Altai Mountains, Russia) revealed in a primary ecological succession	Ecology and Evolution	Asia
Jinag et al.	2018	Unravelling community assemblages through multi-element stoichiometry in plant leaves and roots across primary successional stages in a glacier retreat area	Plant soil	Asia
D´Amico et al.	2017	Primary vegetation succession and the serpentine syndrome: the proglacial area of the Verra Grande glacier, North-Western Italian Alps	Plant soil	European Alps
Fickert	2017	Glacier forelands-unique field laboratories for the study of primary succession of plants	Glaciers Evolution in a Changing World (book)	European Alps
Fickert et al.	2017	Klebelsberg revisited: did primary succession of plants in glacier forelands a century ago differ from today?	Alpine Botany	European Alps
Sitzia et al.	2017	Landscape metrics as functional traits in plants: perspectives from a glacier foreland	PeerJ	European Alps
Görannsson et al.	2016	Nitrogen and phosphorus availability at early stages of soil development in The Damma glacier forefield, Switzerland; implications for establishment of N_2-fixing plants	Plant soil	European Alps
Erschbamer & Caccianiga	2016	Glacier forelands: Lessons of plant population and community development	Progress in Botany	European Alps
Schuhmann et al.	2016	Factors affecting primary succession of glacier foreland vegetation in the European Alps	Alpine Botany	European Alps
Tampuccini et al.	2015	Plant and arthropod colonisation of a glacier foreland in a peripheral mountain range	Biodiversity	European Alps
Carlson et al.	2014	Accounting for tree line shift, glacier retreat and primary succession in mountain plant distribution models	Diversity and Distributions	European Alps
D´Amico et al.	2014	Vegetation influence on soil formation rate in a proglacial chronosequence (Lys Glacier, NW Italian Alps)	Catena	European Alps
Fischer	2013	Long-term glacier monitoring at the LTER test sites Hintereisferner, Kesselwandferner and Jamtalferner and other glaciers in Tyrol: a source of ancillary information for biological succession studies	Plant Ecology & Diversity	European Alps
Burga et al.	2010	Plant succession and soil development on the foreland of the Morteratsch glacier (Pontresina, Switzerland): Straight forward or chaotic?	Flora	European Alps
Robbins & Matthews	2010	Regional variation in successional trajectories and rates of vegetation change on glacier forelands in south-central Norway	Arctic, Antarctic, and Alpine Research	Scandinavia
Jones & Del Moral	2009	Dispersal and establishment both limit colonization during primary succession on a glacier foreland	Plant Ecology	N-America
Dolezal et al.	2008	Primary succession following deglaciation at Koryto Glacier valley, Kamchatka	Arctic, Antarctic, and Alpine Research	Asia
Raffl et al.	2006	Vegetation succession pattern and diversity changes in a glacier valley, Central Alps, Austria	Arctic, Antarctic, and Alpine Research	European Alps

Author	Year	Title	Journal	Location
Mizuno	2005	Glacial fluctuation and vegetation succession on Tyndall Glacier, Mt Kenya	Mountain Research and Development	Africa
Caccianiga & Andreis	2004	Pioneer herbaceous vegetation on glacier forelands in the Italian Alps	Phytocoenologia	European Alps
Raffl & Erschbamer	2004	Comparative vegetation analyses of two transects crossing a characteristic glacier valley in the Central Alps	Phytocoenologia	European Alps
Kaufmann & Raffl	2002	Diversity in primary succession: the chronosequence of a glacier foreland	Global Mountain Biodiversity: A Global Assessment (book)	European Alps
Andreis et al.	2001	Vegetation and environmental factors during primary succession on glacier forelands: some outlines from the Italian Alps	Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology	European Alps
Burga	1999	Vegetation development on the glacier forefield Morteratsch (Switzerland)	Applied Vegetation Science	European Alps
Frenot et al.	1998	Primary succession on glacier forelands in the subantarctic Kerguelen Islands	Journal of Vegetation Science	Antarctic
Mizuno	1998	Succession processes of alpine vegetation in response to glacial fluctuations of Tyndall Glacier, Mt. Kenya, Kenya	Arctic and Alpine Research	Africa
Vetaas	1994	Primary succession of plant assemblages on a glacier foreland-Bodalsbreen, southern Norway	Journal of Biogeography	Scandinavia
Matthews & Whittaker	1987	Vegetation succession on the Storbreen glacier foreland, Jotunheimen, Norway: a review	Arctic and Alpine Research	Scandinavia

Table S2: Meteorological and snow observation stations. Measured variables: P = Precipitation, T = Temperature, WS = Wind speed, H = Humidity, R = Radiation, SD = Snow depth (1 Autonomous Province of Bozen/Bolzano - South Tyrol; 2 Institute of Atmospheric and Cryospheric Sciences, University of Innsbruck).

Station	Acronym	Elevation [m a.s.l.]	Latitude	Longitude	Measured variables	Resolution	Temporal coverage	Valley	Provider
Madtrisch	-	2825	46.4938	10.6144	P, T, WS, H, R, SD	10-min	2000-2020	Sulden	1
Rossbänke	-	2255	46.46935	10.81944	T, H, WS, SD	10-min	2015-2020	Ulten	1
Zufall	-	2265	46.48129	10.67802	SD	Weekly (manual)	2004-2020	Martell	1
Zufritt	-	1851	46.50906	10.72507	P, T, SD	Daily	1980-2020	Martell	1
Hintermartell	HI	1720	46.5169	10.7269	P, T, WS, H, R	10-min	2009-2020	Martell	1
Langenferner-Felsköpfl	LA	2967	46.47245	10.61391	P, T, WS, H, R	10-min	2012-2020	Martell	2
Schöntaufspitze	SC	3328	46.5029	10.6286	T, WS	10-min	1998-2020	Martell	1
Sulden	SU	1907	46.5159	10.5953	P, T, WS, H, R	10-min	1987-2020	Sulden	1
Ulten Weißbrunn	UL	1900	46.4868	10.8318	P, T, H, R	10-min	1987-2020	Ulten	1

Station	**Acronym**	**Elevation [m a.s.l.]**	**Latitude**	**Longitude**	**Measured variables**	**Resolution**	**Temporal coverage**	**Valley**	**Provider**
Weißbrunnspitze	WE	3252	46.494	10.774	T, H, WS	10-min	2012-2020	Ulten	1

Table S3: Overview of data sources considered for the reconstruction of the glacier terminus position, necessary for the determination of the time of deglaciation of the vegetation plots, in the Martell valley (Fürkeleferner [FF], *ZF*: Zufallferner [ZF], Langenferner [LF]). The years refer to the time of the glacier survey/illustration in the respective data source.

Martell valley	
Year	Data source
LIA [FF, ZF]	Morphological mapping: *based on field observations, ALS-DTM (2019) and orthophotos*
1870/71 [FF, ZF]	Map: *3rd Federal survey, 5445/2; 1:25.000, KuK Military Geographical Institute (Austrian Federal Office of Surveying and Metrology - BEV, Austria)*
1887 [FF, ZF]	Map: *3rd Federal survey (reamb.), 5445/2; 1:25.000. KuK Military Geographical Institute (Austrian Federal Office of Surveying and Metrology - BEV, Austria)*
1897 [FF, ZF]	Morphological mapping: *based on field observations, ALS-DTM (2019) and literature study (Richter 1889; Finsterwalder 1890; N.N 1891; Finsterwalder 1896; Fritzsch 1900)*
1911 [FF, ZF, LF]	Map: 4th *Federal survey, 5445/2; 1:25.000, KuK Military Geographical Institute (Austrian Federal Office of Surveying and Metrology - BEV, Austria)*
1945 [FF, ZF, LF]	Aerial image *(Italian Military Geographic Institute - IGMI, Italy)*
1954-56 [FF, ZF]	Aerial image *(Autonomous Province of Bozen/Bolzano, South Tyrol, Italy)*
1959-62[FF,ZF, LF]	Map: *Carta d'Italia, Monte Cevetale F°9 III N.E., 1:25.000 Istituto Geografico Militare Italiano (1963) (Archive: Department of Geography, University of Innsbruck)*
1969 [FF, ZF, LF]	Aerial image *(Italian Military Geographic Institute - IGMI, Italy)*
1985 [FF, ZF, LF]	Aerial image *(Autonomous Province of Bozen/Bolzano, South Tyrol, Italy)*
1992-97[FF,Z,F LF]	Aerial image *(Autonomous Province of Bozen/Bolzano, South Tyrol, Italy)*
1999 [FF, ZF, LF]	Aerial image *(Autonomous Province of Bozen/Bolzano, South Tyrol, Italy)*
2003 [FF, ZF, LF]	Aerial image *(Autonomous Province of Bozen/Bolzano, South Tyrol, Italy)*
2005 [FF, ZF, LF]	ALS-DTM *(Autonomous Province of Bozen/Bolzano, South Tyrol, Italy)*
2006 [FF, ZF, LF]	Aerial image *(Autonomous Province of Bozen/Bolzano, South Tyrol, Italy)*
2008 [FF, ZF, LF]	Aerial image *(Autonomous Province of Bozen/Bolzano, South Tyrol, Italy)*
2011 [FF, ZF, LF]	ALS-DTM *(Autonomous Province of Bozen/Bolzano, South Tyrol funded project MALS)*
2013 [FF, ZF, LF]	ALS-DTM *(Department of Atmospheric and Cryospheric Sciences, University of Innsbruck;* (Galos et al., 2015)
2017 [FF, ZF, LF]	Aerial image (*Google Earth*)
2019 [FF, ZF, LF]	ALS-DTM *(Department of Physical Geography, Catholic University of Eichstätt-Ingolstadt; DFG & FWF-funded project SEHAG)*

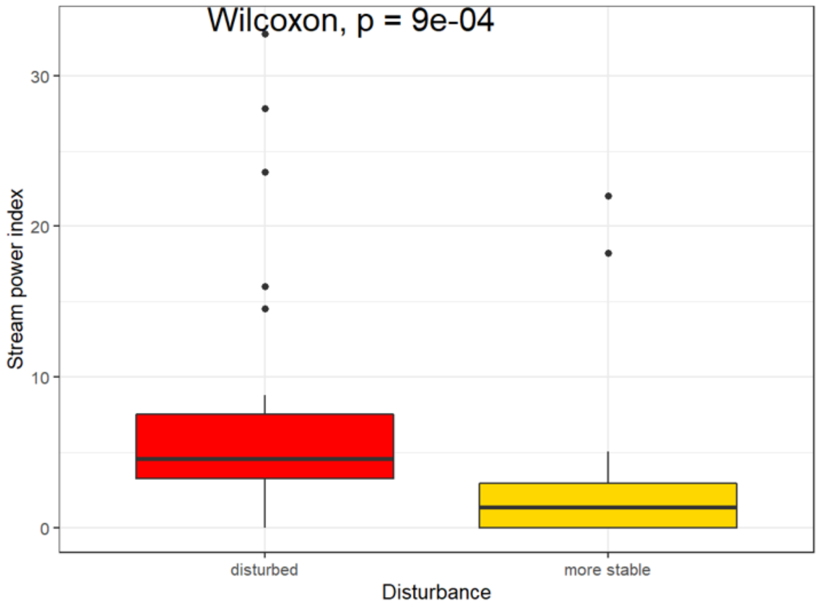


Figure S2: Boxplot of the Stream power index (SPI) (log-transformed for better visibility) for disturbed (red) and more stable (yellow) plots. Wilcox rank tests are performed for analysis of significance of difference between disturbance groups.

Table S4: Sources for livestock numbers in Martell.

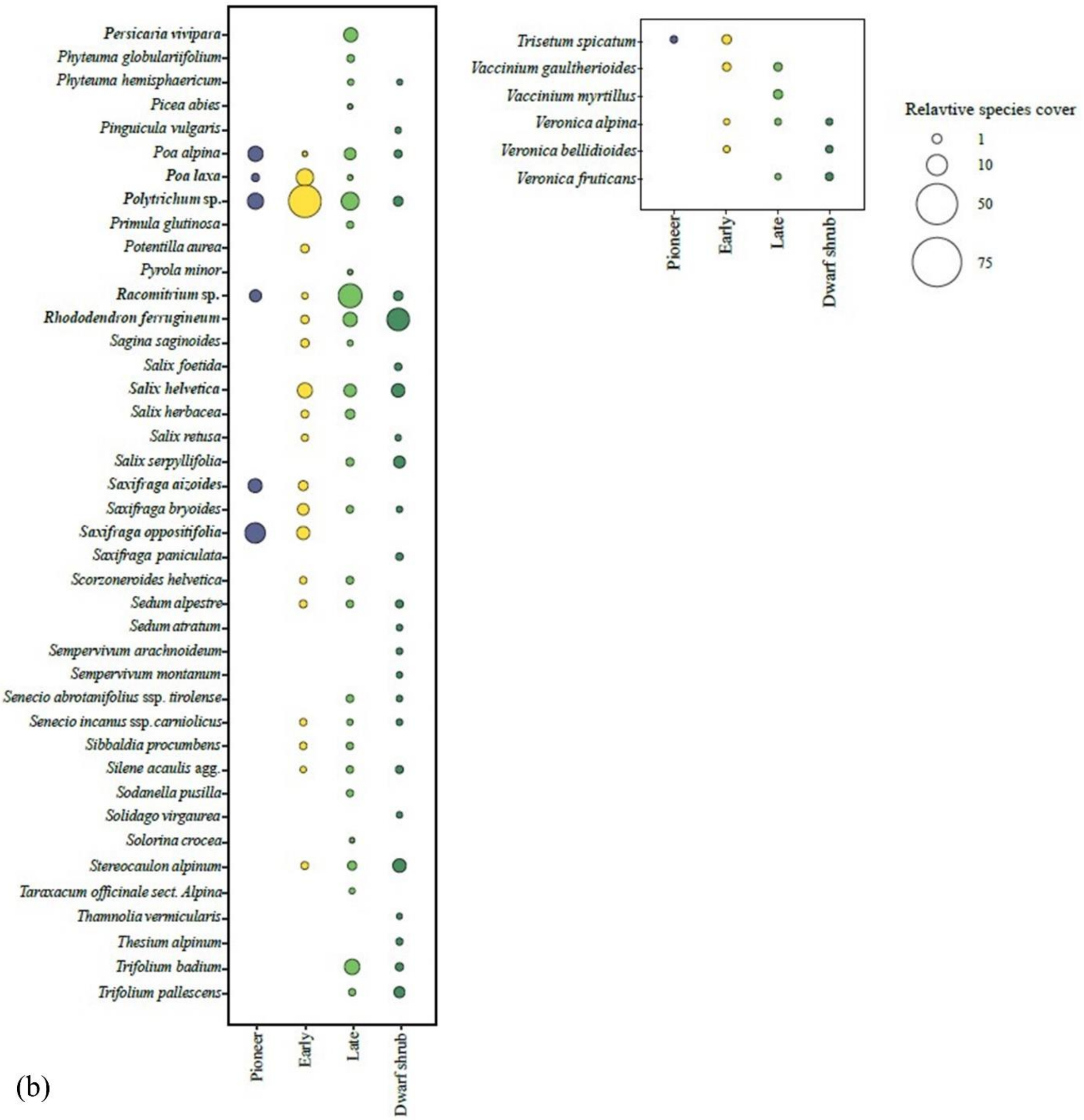
Year	Source
1869	Graf Belrupt (1871)
1900	Tasser et al. (2012)
1910	Tasser et al. (2012)
1930	Fischer (1974)
1955	Fischer (1974)
1959	Fischer (1974)
1970	Fischer (1974)
1982	Landesinstitut für Statistik, Istituto Centrale Di Statistica, Central Institute of Statistics, Istat, and I.S.T.A.T. (1984)
1990	astat (1990)
2000	Autonome Provinz Bozen-Südtirol, Landesinstitu für Statistik - ASTAT (2013)
2010	(Autonome Provinz Bozen-Südtirol, Landesinstitu für Statistik - ASTAT, 2013)

Table S5: Result of the varimax rotated PCA with the results for the different components (RC) with the SS loadings (eigenvalues), proportion variance (how much of the overall variance the component accounts for), proportion explained (relative amount of variance explained) and the cumulative values for the proportion variance and proportion explained, sorted concerning the proportion of variance explained.

	RC1	**RC2**	**RC3**	**RC4**	**RC5**
SS loadings	11.66	4.52	4.33	3.25	2.67
Proportion Variance	0.35	0.14	0.13	0.10	0.08
Cumulative Variance	0.35	0.49	0.62	0.72	0.80

Achillea moschata
Achillea nana
Agrostis alpina
Agrostis agrostiflora
Agrostis rupestris
Alchemilla vulgaris agg.
Anthoxanthum odoratum
Anthyllis vulneraria ssp. alpicola
Arabis caerulea
Arctostaphylos uva-ursi
Arenaria biflora
Athyrium distenifolium
Atocion rupestre
Avenella flexuosa
Avenula versicolor
Bartsia alpina
Calluna vulgaris
Campanula scheuchzeri
Cardamine alpina
Cardamine resedifolia
Carex atrata
Carex curvula
Cerastium cerastoides
Cerastium fontanum
Cerastium pedunculatum
Cerastium uniflorum
Cetraria islandica
Chlorocrepis staticifolia
Cirsium spinosissimum
Cladonia arbuscula
Cladonia rangiferina
Cladonia sp.
Cystopteris fragilis
Daphne striata
Diphasiastrum alpinum
Doronicum clusii
Draba aizoides
Draba fladnizensis
Dryas octopetala
Dryopteris filix-mas
Empetrum hermaphroditum
Epilobium angustifolium
Epilobium fleischeri
Epilobium nutans
Pioneer
Early
Late
Dwarf shrub
Euphrasia minima agg.
Festuca halleri
Festuca intercedens
Flavocetraria cucullata
Flavocetraria nivalis
Galium anisophyllon
Gentiana nivalis
Gentiana verna
Geum reptans
Gnaphalium supinum
Hieracium alpinum
Hieracium pilosella
Hieracium murorum
Hieracium sp.
Hieracium sphaerocephalum
Homogyne alpina
Huperzia selago
Juncus jacquinii
Juncus trifidus
Juniperus communis ssp. nana
Kobresia myosuroides
Lichens
Larix decidua
Leontodon hispidus
Leucanthemopsis alpina
Linaria alpina
Lloydia serotina
Loiseleuria procumbens
Luzula alpinopilosa
Luzula lutea
Luzula multiflora
Luzula spicata
Minuartia biflora
Minuartia gerardii
Minuartia recurva
Minuartia sedoides
Mosses
Myosotis alpestris
Nardus stricta
Oreochloa disticha
Oxyria digyna
Pedicularis kerneri
Pioneer
Early
Late
Dwarf shrub
Relavtive species cover
1
10
50
75

(a)



(b)

Figure S3a and b: Species list with the species assigned to the four main successional stages (Pioneer = pioneer stage, Early = early successional stage, Late = late successional stage (incl. both groups), Dwarf sh.(shrub) = dwarf shrub stage). The circles are according to the relative cover of each species in each stage and the different colours also indicate the different stages.

Table S6: Species list with the species assigned to the four main successional stages (Pioneer = pioneer stage, Early = early successional stage, Late = late successional stage (incl. both groups), Dwarf sh.(shrub) = dwarf shrub stage). The circles are according to the relative cover of each species in each stage and the different colours also indicate the different stages species with relative cover > 4 % are highlighted in bold.

Species	**Pioneer stage**	**Early stage**	**Late stage**	**Dwarf-shrub stage**
Achillea moschata			0.17	2.37
Achillea nana		0.45	0.78	
Agrostis alpina		0.60		
Agrostis agrostiflora		0.55		0.18
Agrostis rupestris		4.83	2.37	0.19
Alchemilla vulgaris agg.				

Anthoxanthum odoratum			0.12	
Anthyllis vulneraria ssp. *alpicola*				0.40
Arabis caerulea		0.47		
Arctostaphylos uva-ursi				**6.48**
Arenaria biflora		0.19	0.50	
Athyrium distenifolium			0.96	
Atocion rupestre				0.53
Avenella flexuosa				0.49
Avenula versicolor			0.60	
Bartsia alpina			0.62	
Calluna vulgaris				1.36
Campanula scheuchzeri			0.64	
Cardamine alpina		1.00	0.67	
Cardamine resedifolia	0.12	0.14	0.17	0.76
Carex atrata			0.12	
Carex curvula			0.17	
Cerastium cerastoides		0.56		
Cerastium fontanum			0.45	
Cerastium pedunculatum		1.94	0.53	
Cerastium uniflorum		3.63	0.16	
Cetraria islandica		0.17	0.53	**5.52**
Chlorocrepis staticifolia				1.56
Cirsium spinosissimum			1.13	
Cladonia arbuscula			0.42	0.22
Cladonia rangiferina			0.43	0.18
Cladonia sp.		0.14		0.12
Cystopteris fragilis		0.19		
Daphne striata				0.19
Diphasiastrum alpinum			0.28	
Doronicum clusii		0.38		
Draba aizoides				0.18
Draba fladnizensis		0.17		
Dryas octopetala				0.33
Dryopteris filix-mas			0.48	
Empetrum hermaphroditum			0.39	**4.13**
Epilobium angustifolium			0.67	
Epilobium fleischeri				0.16
Epilobium nutans			0.46	
Erigeron uniflorus				
Euphrasia minima agg.		1.72	0.47	0.12
Festuca halleri		0.69	0.50	4.28
Festuca intercedens				0.26
Flavocetraria cucullata				0.18
Flavocetraria nivalis		0.25		0.38
Galium anisophyllon			0.16	
Gentiana nivalis				0.76
Gentiana verna				0.35
Geum reptans			0.18	
Gnaphalium supinum		1.22	0.56	0.16

Hieracium alpinum		0.40	0.24	0.32
Hieracium pilosella		0.12	0.89	0.43
Hieracium murorum				0.37
Hieracium sp.			0.25	
Hieracium sphaerocephalum				0.28
Homogyne alpina		0.27		
Huperzia selago		0.42	0.49	
Juncus jacquinii			0.52	
Juncus trifidus			0.38	0.53
Juniperus communis ssp.*nana*			0.47	0.42
Kobresia myosuroides			0.99	
Lichens		0.47	**6.29**	0.37
Larix decidua	0.43	0.56	1.63	4.36
Leontodon hispidus			0.35	
Leucanthemopsis alpina		0.37	0.17	0.27
Linaria alpina		2.82		
Lloydia serotina		0.16		
Loiseleuria procumbens			0.27	3.72
Luzula alpinopilosa			**12.95**	
Luzula lutea				3.52
Luzula multiflora			0.29	0.18
Luzula spicata		0.19	0.18	0.88
Minuartia biflora		0.11		
Minuartia gerardii		0.34		0.12
Minuartia recurva		0.15		
Minuartia sedoides			0.95	0.16
Mosses	**31.49**	**11.42**	**9.59**	1.93
Myosotis alpestris			0.59	
Nardus stricta			0.78	
Oreochloa disticha			0.34	
Oxyria digyna			0.16	
Pedicularis kerneri			0.63	
Persicaria vivipara			**4.48**	
Phyteuma globulariifolium			0.58	
Phyteuma hemisphaericum			0.24	0.16
Picea abies			0.12	
Pinguicula vulgaris				0.25
Poa alpina	5.56	0.12	2.67	0.69
Poa laxa	0.78	**7.92**	0.14	
***Polytrichum* sp.**	**6.51**	**36.64**	**8.51**	1.44
Primula glutinosa			0.45	
Potentilla aurea		0.94		
Pyrola minor			0.11	
***Racomitrium* sp.**	2.84	0.29	**17.58**	1.31
Rhododendron ferrugineum		0.86	**4.69**	**15.37**
Sagina saginoides		0.91	0.18	
Salix foetida				0.53
Salix helvetica		5.34	3.21	3.86
Salix herbacea		0.65	1.39	

Salix retusa		0.44		0.26
Salix serpyllifolia			0.77	2.65
Saxifraga aizoides	4.39	1.47		
Saxifraga bryoides		2.51	0.50	0.25
Saxifraga oppositifolia	**11.99**	3.62		
Saxifraga paniculata				0.53
Scorzoneroides helvetica		0.49	0.59	
Sedum alpestre		0.64	0.52	0.66
Sedum atratum				0.26
Sempervivum arachnoideum				0.30
Sempervivum montanum				0.22
Senecio abrotanifolius ssp. *tirolense*			0.58	0.26
Senecio incanus ssp. *carniolicus*		0.45	0.23	0.29
Sibbaldia procumbens		0.52	0.46	
Silene acaulis agg.		0.25	0.47	0.63
Sodanella pusilla			0.42	
Solidago virgaurea				0.25
Solorina crocea			0.12	
Stereocaulon alpinum		0.60	1.13	3.96
Taraxacum officinale sect. Alpina			0.18	
Thamnolia vermicularis				0.16
Thesium alpinum				0.43
Trifolium badium			**5.74**	0.77
Trifolium pallescens			0.45	2.17
Trisetum spicatum	0.32	0.94		
Vaccinium gaultherioides		0.63	0.62	
Vaccinium myrtillus			0.89	
Veronica alpina		0.12	0.22	0.25
Veronica bellidioides		0.24		0.34
Veronica fruticans			0.13	0.49

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