Vegetation colonization of permafrost-related landslides, Ellesmere Island, Canadian High Arctic

Nicoletta Cannone,[1,2] Antoni G. Lewkowicz,[3] and Mauro Guglielmin[4]

Received 7 April 2010; revised 25 June 2010; accepted 2 July 2010; published 11 November 2010.

[1] Relationships between vegetation colonization and landslide disturbance are analyzed for 12 active-layer detachments of differing ages located in three areas of the Fosheim Peninsula, Ellesmere Island (80°N). We discuss vegetation as an age index for landslides and a way to assess the time needed for complete recolonization of the surfaces since landslide detachment. Vegetation on undisturbed terrain is similar in the three areas but is more highly developed and complex inland due to a warmer summer climate. On a regional scale, the location of the area is as important as the effect of landslide age on vegetation colonization because of the influence of mesoclimatic conditions on vegetation development. On a landscape scale, there is a positive relationship between landslide age and vegetation development, as represented by total vegetation cover, floristic composition, and successional stage. Consequently, vegetation can be used at this scale as an indicator of landslide age. Fifty years are required to restore vegetation patches to a floristic composition similar to communities occurring in undisturbed conditions, but with lower floristic richness and a discontinuous cover and without well-developed layering. The shorter time needed for landslide recovery in the area with the warmest summer climate confirms the sensitivity of arctic vegetation to small differences in air temperature. This could trigger a set of interlinked feedbacks that would amplify future rates of climate warming.

Citation: Cannone, N., A. G. Lewkowicz, and M. Guglielmin (2010), Vegetation colonization of permafrost-related landslides, Ellesmere Island, Canadian High Arctic, *J. Geophys. Res.*, *115*, G04020, doi:10.1029/2010JG001384.

1. Introduction

[2] Landslides occur in virtually every terrestrial environment from the poles to the equator. There is mounting evidence that the frequency and magnitude of landsliding is likely to increase in many parts of the world over the next century as the global climate warms [*IPCC*, 2007; *Restrepo et al.*, 2009]. Landslides may be triggered by meteorological events such as episodic heavy rainfall, particularly rapid snowmelt, and rapid thaw of the active layer or the top layers of permafrost (perennially frozen ground) in Arctic areas [*Lewkowicz*, 1990, 1992, 2007; *Leibman*, 1995; *Schuur et al.*, 2007; *Lantz et al.*, 2009]. In permafrost areas, slope instability may increase as permafrost degrades and the active layer becomes thicker [*Dyke*, 2000; *Harris and Lewkowicz*, 2000] or as changes occur in the frequency of short periods of summer warming [*Lewkowicz and Harris*, 2005a; *Lewkowicz*, 2007; *Lamoureux and Lafrenière*, 2009] or intense precipitation.

[3] Landslides are an important disturbance factor affecting vegetation composition and development. Studies focused on patterns of recolonization and mechanisms of succession on disturbed surfaces of different ages [*Reddy and Singh*, 1993; *Lewis*, 1998], demonstrate that both species number and biomass increase with time since landsliding [*Dalling*, 1994]. Consequently, the vegetation on unstable sites has a different floristic composition from adjacent stable areas [*Nagamatsu and Miura*, 1997]. Within each landslide the colonization patterns are heterogeneous: disturbance to vegetation is greatest in the upper erosional zone [*Guariguata*, 1990], where conditions are harshest [*Dalling*, 1994], while rates of vegetation development are highest in the depositional zone [*Walker et al.*, 1996]. Vegetation colonization is determined by the availability of propagules [*Walker et al.*, 1996], but is also influenced by plants that survive on transported blocks, microsite availability, and the source of seeds.

[4] Arctic ecosystems are especially sensitive to both natural and anthropogenic disturbance and their vulnerability increases toward the poles as ecosystems become simpler and biodiversity decreases [e.g., *Chapin and Körner*, 1995; *Walker and Walker*, 1991; *IPCC*, 2001]. Studies on vegetation disturbance in Arctic areas have shown that the impact of disturbances depend on the type, intensity, and frequency of perturbation and the capability and rate of vegetation

[1]Department of Biology and Evolution, Ferrara University, Ferrara, Italy.
[2]Now at Department of Chemical and Environmental Sciences, University of Insubria, Como, Italy.
[3]Department of Geography, University of Ottawa, Ottawa, Ontario, Canada.
[4]DBSF, University of Insubria, Varese, Italy.

0148-0227/10/2010JG001384

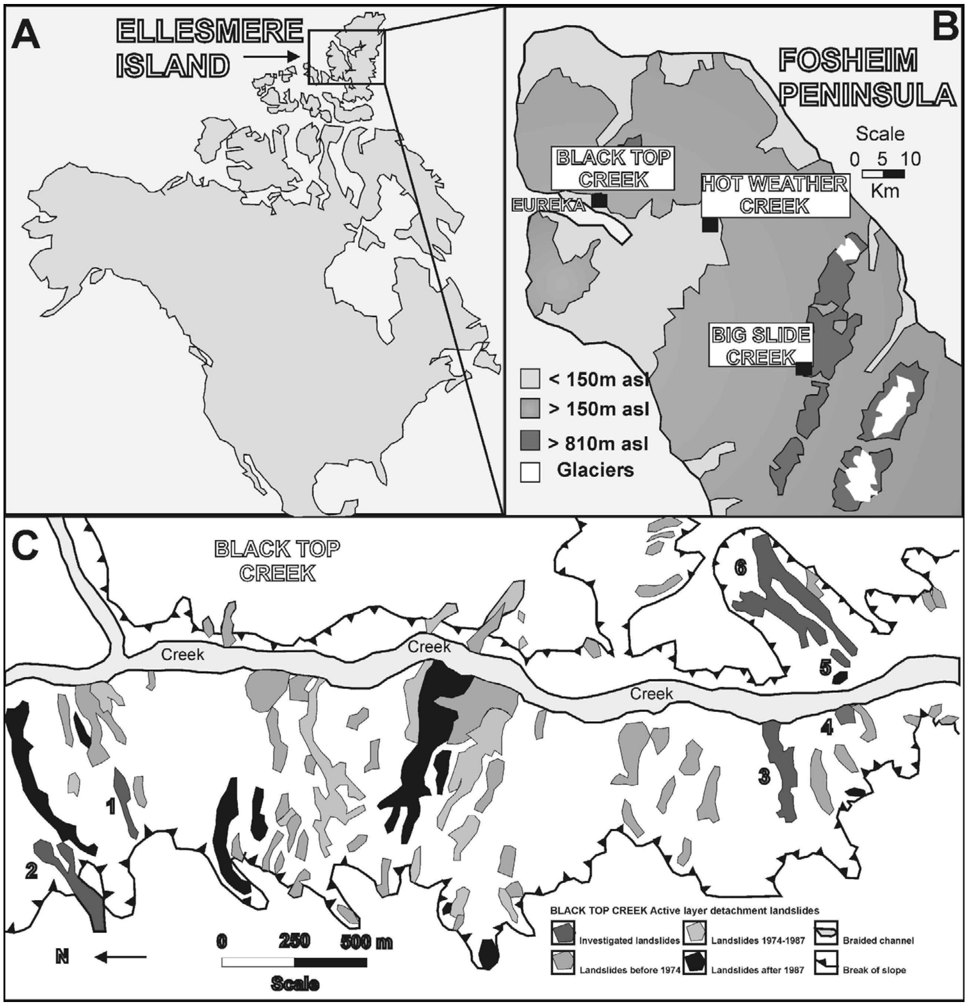

Figure 1. Location map of the study areas (a) in the North American High Arctic, (b) at Fosheim Peninsula (Ellesmere Island, Canada), and (c) at the detailed location of the investigated landslides at Black Top Creek (the area where landslide ages are best constrained and, consequently, vegetation analyses were carried out in greater detail). Legend of the landslides investigated at Black Top Creek: 1, before 1950; 2, 1950–1959; 3, 1959–1974; 4, 1987; 5, 1997–1998; 6, 1997–1998; pale gray, water (sea and creek).

restoration [e.g., *Hernandez*, 1973; *Babb and Bliss*, 1974; *Walker and Walker*, 1991]. In the Low Arctic, accelerated disturbance regimes have the potential to magnify the effects of warming temperature on vegetation [*Lantz et al.*, 2009]. However, very little research to date has examined the impacts of landsliding (notable exceptions being *Harris and Gustafson* [1993], *Lewis* [1998], *Bartleman et al.* [2001], and *Ukraintseva et al.* [2003]) and, to our knowledge, none has been published for the High Arctic.

[5] This paper aims to (1) analyze the relationship between landslide age and vegetation development at a location in the High Arctic, (2) assess whether this relationship depends on the scale of analysis (landscape or regional, according to *Trivedi et al.* [2008]) or climate (air temperature), and (3) identify the stages of vegetation colonization and development on active-layer detachments (shallow landslides over permafrost). To achieve these aims, we carried out field investigations in three different study areas (Black Top Creek (BTC), Big Slide Creek (BSC), and Hot Weather Creek (HWC)) on Ellesmere Island (Nunavut, Canada) where we analyzed and compared the vegetation of 12 active-layer detachments with that on adjacent undisturbed terrain.

2. Methods

2.1. Study Area

[6] Field investigations were carried out in three study areas on the Fosheim Peninsula, Ellesmere Island, where active-layer detachments have occurred repetitively over at least the past 50 years (Figure 1): BTC (79°58′N, 85°40′W; 10–90 m above sea level (asl)), BSC (unofficial name; 79°42′N, 84°23′W; 150–250 m asl), and HWC (79°58′N, 84°28′W; 50–100 m asl). The climate of the region is cold and dry, with a mean annual temperature of −19.7°C (1971–2000) and annual precipitation of 76 mm at Eureka located next to Slidre Fiord (Environment Canada data, http://www.climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html, accessed on 1 August 2009). However, summer air

Table 1. Study Area, Feature, and Landslide Detachment Period and Number of Vegetation Surveys[a]

	BSC, U	BSC, L1, 1987	BSC, L2, 1987	BSC, L3, 1987	BSC, L, 1997	BTC, U	BTC, L, <1950	BTC, L, 1950–1959	BTC, L, 1959–1974	BTC, L, 1987	BTC, L1, 1997	BTC, L2, 1997	HWC, U	HWC, L 1987	HWC, L 1988
Number of vegetation surveys	32	20	20	15	22	18	15	33	31	29	18	10	16	20	17

[a]The number of vegetation surveys is given for each combination of area, feature, and detachment year (e.g., BSC, L1, 1987). L, landslide; U, undisturbed; BSC, Big Slide Creek; BTC, Black Top Creek; HWC, Hot Weather Creek. Landslides of the same age in the same area were numbered consecutively (e.g., L1, L2, and L3 at BSC).

temperatures are relatively high for this latitude, reaching an average of 5.7°C for July at Eureka, and temperatures are still greater away from coastal influences [e.g., *Atkinson*, 2000].

[7] The bedrock at BTC comprises poorly lithified shales, siltstones, sandstones, and mudstones of the Mesozoic Isachsen Formation, while at both BSC and HWC it includes sandstones, siltstones, shales, and coal of the Tertiary Eureka Sound Formation [*Geological Survey of Canada*, 1971]. Clays and silts of marine, glacial, and colluvial origin and residual materials derived from the weathering of bedrock mantle most slopes. BTC and HWC are located below the Holocene marine limit of 140 m asl [*Bell*, 1996], while BSC lies above it. Permafrost is continuous and extends to depths of 500 m or more [*Heginbottom et al.*, 1995]. Active-layer thicknesses range from 0.5 to 0.9 m, with the highest values in sandy soils.

[8] The study areas are located in bioclimatic subzone C of Arctic tundra [*Gould et al.*, 2003] and exhibit prostrate dwarf shrub tundra and prostrate dwarf shrub graminoid tundra vegetation complexes. Vegetation comprises both polar desert, with a predominance of *Luzula* barrens, and polar semidesert [*Bliss and Svoboda*, 1984; *Bliss et al.*, 1984] mostly dominated by the Graminoid steppe with *Luzula confusa* and *Alopecurus alpinus* [*Bliss and Svoboda*, 1984; *Muc et al.*, 1994] or *Luzula* tundra *sensu* [*Edlund and Alt*, 1989]. The prostrate dwarf shrub tundra is characterized by the occurrence of *Salix*-*Luzula* barrens, and *Dryas*-*Salix* tundra and barrens [*Edlund and Alt*, 1989; *Gould et al.*, 2002] occur in more favorable conditions, while a *Salix arctica*-*Cassiope tetragona* community [*Batten and Svoboda*, 1984] develops locally on slopes with deep snow banks.

[9] Several hundred active-layer detachments have been mapped and monitored in the three areas since 1988 [*Lewkowicz*, 1990, 1992], their form and internal structure have been described [e.g., *Lewkowicz and Harris*, 2005b], and their frequency, magnitude, triggers, and links to climate have been examined [e.g., *Lewkowicz and Harris*, 2005a; *Lewkowicz*, 2007].

2.2. Field Measurements and Data Elaboration

[10] Twelve active-layer detachments with ages varying from more than 50 years (predating 1950 based on aerial photographic interpretation) to 2–3 years (dating to 1997–1998 based on field monitoring since 1988) were selected for detailed study in July 2000 (Table 1). Vegetation surveys were carried out within the landslides, sampling all of the morphological features. For comparison, randomly located vegetation surveys were undertaken to describe the most common vegetation communities in undisturbed areas located within a 250 m radius of the landslides. This is the typical maximum distance between the neighboring landslides on slopes in the study area and is also comparable to the size of many of the landslides investigated.

[11] Vegetation was sampled in homogeneous 2 × 2 m quadrants that were representative of the different vegetation types and located in microtopographically homogeneous conditions. Total vegetation cover and the cover of each vascular species and the general categories of mosses and lichens were estimated visually within every quadrant. Species nomenclature follows *Porsild* [1957] and *Porsild and Cody* [1980] for vascular plants.

[12] Given the large number of vegetation surveys, we omitted the relevés without any vegetation prior to further data analysis. In addition, the species matrix was simplified, omitting 21 species that occurred in less than 5% of the relevés or constituted less than 1% cover. The modified set used for data elaboration included 250 relevés on landslides, 66 relevés on undisturbed terrain, and 33 species in the three study areas.

[13] Relationships between landslide age and vegetation were analyzed on a landscape scale (0.0025–25 km^2) and regional scale (25–2500 km^2) [see *Trivedi et al.*, 2008, and references therein]. For the latter, the relations between area location and vegetation characteristics were examined for undisturbed conditions (n = 66) at the three study areas (BSC, BTC, HWC) using multivariate analyses with redundancy analysis (RDA). On the same scale, the relations between landslide occurrence (undisturbed sites versus landslides), age, and vegetation characteristics on a regional scale were investigated at all three study tables (n = 316, involving all landslides and undisturbed sites) using RDA. On the landscape scale, the relations between landslide age and vegetation characteristics were investigated by RDA at Black Top Creek. This area provided well-constrained ages of landslides (from 2 to 3 years to >50 years; n = 136) due to more frequent air photo coverage.

[14] Two matrices were used for all RDAs: (1) a species matrix, reporting total vegetation cover and the cover of dominant species, and (2) an environmental matrix, reporting the feature type, undisturbed terrain or landslide, landslide age, and area location. RDA were carried out without data transformation prior to analysis and performed using CANOCO software version 4 [*Ter Braak and Šmilauer*, 1998].

3. Results

[15] A total of 54 species of vascular plants were identified, plus the general categories of mosses, lichens, and black cryptogamic crust. The vascular plant species colo-

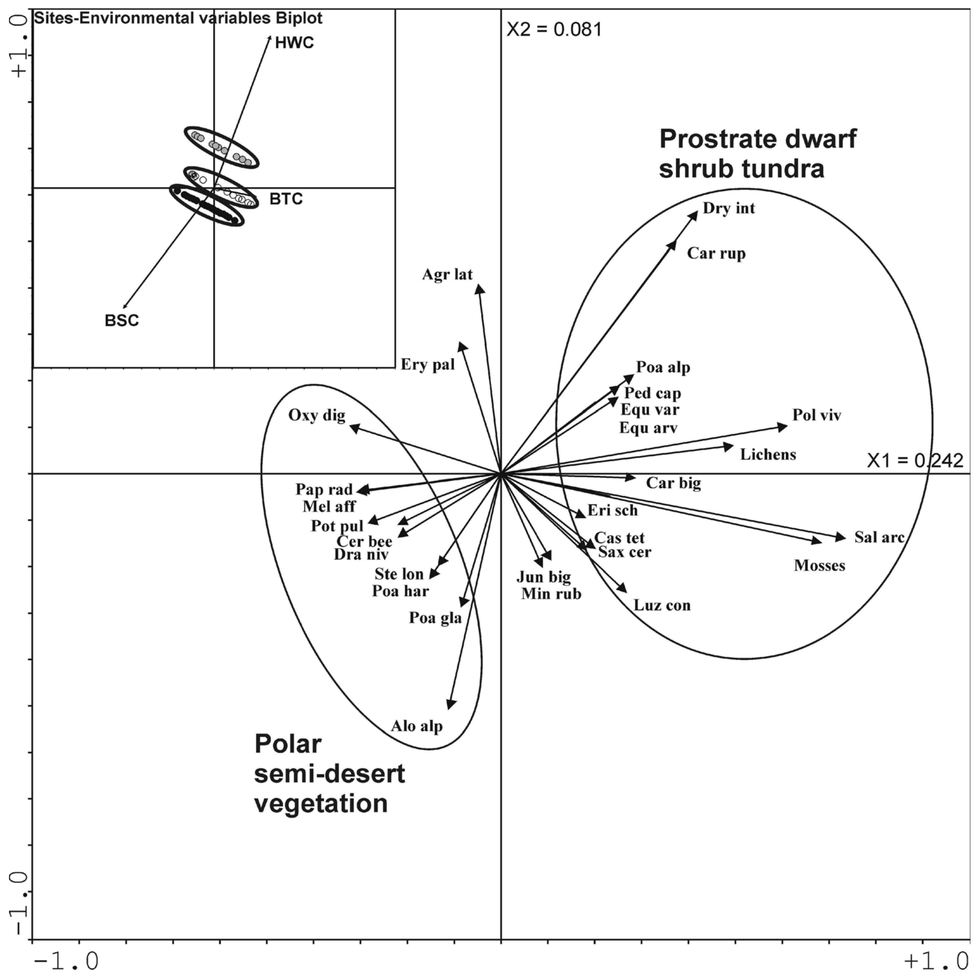

Figure 2. Multivariate analysis (redundancy analysis (RDA)) of the vegetation surveys carried out in undisturbed conditions (outside landslides) within the three study areas: Big Slide Creek (BSC, black circles), Black Top Creek (BTC, white circles), Hot Weather Creek (HWC, gray circles), see also Table 2. Agr lat, *Agropyron latiglume*; Alo alp, *Alopecurus alpinus*; Car big, *Carex bigelowii*; Car rup, *Carex rupestris*; Cas tet, *Cassiope tetragona*; Cer bee, *Cerastium beeringianum*; Dra niv, *Draba nivalis*; Dry int, *Dryas integrifolia*; Equ var, *Equisetum variegatum*; Eri sch, *Eriophorum scheuchzeri*; Ery pal, *Erysimum pallasii*; Jun big, *Juncus biglumis*; Luz con, *Luzula confusa*; Luz niv, *Luzula nivalis*; Mel aff, *Melandrium affine*; Min rub, *Minuartia rubella*; Oxy dig, *Oxyria digyna*; Pap rad, *Papaver radicatum*; Ped cap, *Pedicularis capitata*; Poa alp, *Poa alpigena*; Poa gla, *Poa glauca*; Poa har, *Poa hartzii*; Pol viv, *Polygonum viviparum*; Pot pul, *Potentilla pulchella*; Sal arc, *Salix arctica*; Sax cer, *Saxifraga cernua*; Sax tri, *Saxifraga tricuspidata*; Ste lon, *Stellaria longipes*; Tri spi, *Trisetum spicatum*.

nizing the landslides constitute about half the species occurring in this bioclimatic zone [*Edlund and Alt*, 1989; *Gould et al.*, 2002, 2003].

3.1. Vegetation in Undisturbed Conditions

[16] The RDA for undisturbed locations (Figure 2 and Tables 1 and 2) shows three clusters of vegetation surveys corresponding to the differing locations of the three areas characterized by a progressive shift in floristic composition from polar semideserts to prostrate dwarf shrub tundra. The vegetation types occurring on undisturbed terrain are: (1) polar semideserts [*Bliss and Svoboda*, 1984; *Bliss et al.*, 1984; *Muc et al.*, 1994], mainly composed of *Luzula* barrens dominated by *Luzula confusa* and *Alopecurus alpinus* with rosette plants (*Saxifraga*, *Draba*) as companion species; and (2) prostrate dwarf shrub tundra [*Batten and Svoboda*, 1984; *Edlund and Alt*, 1989] with *Salix arctica*, *Luzula confusa*, *L. nivalis*, *Dryas integrifolia*, and, locally, *Cassiope tetragona*.

[17] At BSC, the vegetation is mainly polar semidesert with *Alopecurus alpinus* barrens (Table 2). Two vegetation communities are associated with specific edaphic conditions in this area: (1) communities dominated by *Poa hartzii* colonizing sites where ground drainage is limited due to the occurrence of alluvial clay; and (2) communities dominated by *Poa glauca* on exposed sites with clast-rich sandstone regolith or colluvium. At BTC, prostrate dwarf shrub tundra is dominated by *Salix arctica* and mosses, with the lowest number of vascular plant species of the three locations. HWC exhibits the richest and most complex vegetation, mainly composed of prostrate dwarf shrub tundra with highly evolved communities, dominated by *Dryas integrifolia* and

Table 2. Cover Percentage of Total Vegetation and Dominant Species of the 2 Main Clusters (Total of 12 Groups) Identified by RDA in Undisturbed Conditions and in All 9 Investigated Landslides in the 3 Study Areas[a]

	S1a, BSC, 1997	S1a, BTC, 1997	S1a, BTC, 1987	S1a, BTC, 1959–1974	S1a, BTC, 1950–1959	S1, BSC, 1987	S2, HWC, 1988	S2, HWC, 1987	S2, BSC, Und	S3, BTC, Pre-1950	S3, BTC, Und	S3, HWC, Und
Total coverage (%)	17	26	33	41	49	43	42	45	46	57	53	63
Poa alpigena	12	24	33	36.5	42.4					6	0.5	2
Poa hartzii	+					25.5			3			
Poa glauca					2	7.5	24	11	6	2	4	1
Alopecurus alpinus	0.5	0.5		1	1	7		2	12	8	2	+
Melandrium affine	+	1		1	1	1	0.5		3	1	10	9
Salix arctica	2				+	+	10	19	11	30	26	21
Dryas integrifolia								5		3	1	17
Mosses									3		10	9
Carex rupestris											0.5	8
Polygonum viviparum									+		2	4
Cassiope tetragona									2		3	
Oxyria digyna									2		1	1
Papaver radicatum									1		0.5	+
Juncus biglumis									0.5			
Pedicularis capitata												0.5
Erigeron compositus var. *discoideus*											0.5	
Minuartia rubella									+		+	
Potentilla pulchella		0.5		1	1	2	2		2	2	+	+
Stellaria longipes	0.5					0.5		5	2	0.5	+	1
Luzula confusa									2		2	
Carex bigelowii											3	1
Trisetum spicatum									+		3	
Eriophorum scheuchzeri									0.5			+
Equisetum arvense												2
Draba nivalis									0.5		+	
Equisetum variegatum												0.5
Saxifraga tricuspidata											1	
Agropyron latiglume												1
Luzula nivalis									+			
Erysimum pallasii												+
Cerastium beeringianum									+		+	
Saxifraga cernua									+			+
Lichens									0.5		3	5

[a]The cover percentage of total vegetation and dominant species is given for each combination of successional stage, area, and landslide detachment period (e.g., S1a, BSC, 1997). BSC, Big Slide Creek; BTC, Black Top Creek; HWC, Hot Weather Creek; Und, undisturbed; +, cover is ≤0.1%.

Salix arctica and barrens with *Carex rupestris*. Some calciphilic species occur locally.

3.2. Landslide Vegetation: Regional Scale (All Areas)

[18] Vegetation floristic composition is strongly related to the existence of disturbance (landslide area versus undisturbed conditions), landslide age, and area location. RDA allows four main groups of species and relevés to be identified (Figure 3 and Table 2): (1) *Poa alpigena*, (2) *Poa hartzii*, (3) *Alopecurus alpinus and Poa glauca*, and (4) *Salix arctica* and *Dryas integrifolia*. These four groups correspond to different successional stages, from the pioneer vegetation occurring on the most recent landslides to the more evolved vegetation on the oldest landslides and at undisturbed sites.

[19] The youngest surfaces are colonized by pioneer communities dominated respectively by *Poa alpigena* (group S1a in Figure 3 and Table 2, mainly located at BTC) and by *Poa hartzii* (group S1b in Figure 3 and Table 2, mainly located at BSC). Group S1a includes all BTC landslides (except the one that is more than 50 years old) and is characterized by pioneer vegetation. All the 2–3 year old landslides show similar average total vegetation cover (~23%) and are dominated by *Poa alpigena*. In about 10 years (landslides 12–13 years old versus 2–3 years old) average total vegetation cover roughly doubles.

[20] The pioneer vegetation is progressively replaced by polar semideserts in transition to the dwarf shrub tundra, composed of more evolved communities dominated by *Poa glauca*, *Salix arctica*, and *Alopecurus alpinus* (group S2 in Figure 3 and Table 2) as shown at landslides older than 13 years at HWC as well as on undisturbed sites (outside landslides) at BSC.

[21] The highest degree of vegetation evolution and successional stage is prostrate dwarf shrub tundra with *Salix arctica*, *Dryas integrifolia*, *Carex rupestris*, and *Polygonum viviparum*, characterizing undisturbed sites at BTC and HWC and the oldest landslide (older than 50 years) at BTC.

[22] The RDA on a regional scale permits reconstruction of the main successional stages of vegetation development (gray and black arrows Figure 3). It appears that the study area location is as important as landslide age in shaping the vegetation characteristics. For example, the vegetation in the two HWC landslides (age 13 years, group S2 of Figure 3 and Table 2), is more similar to that in the oldest landslide at BSC (older than 50 years, group S3 of Figure 3 and

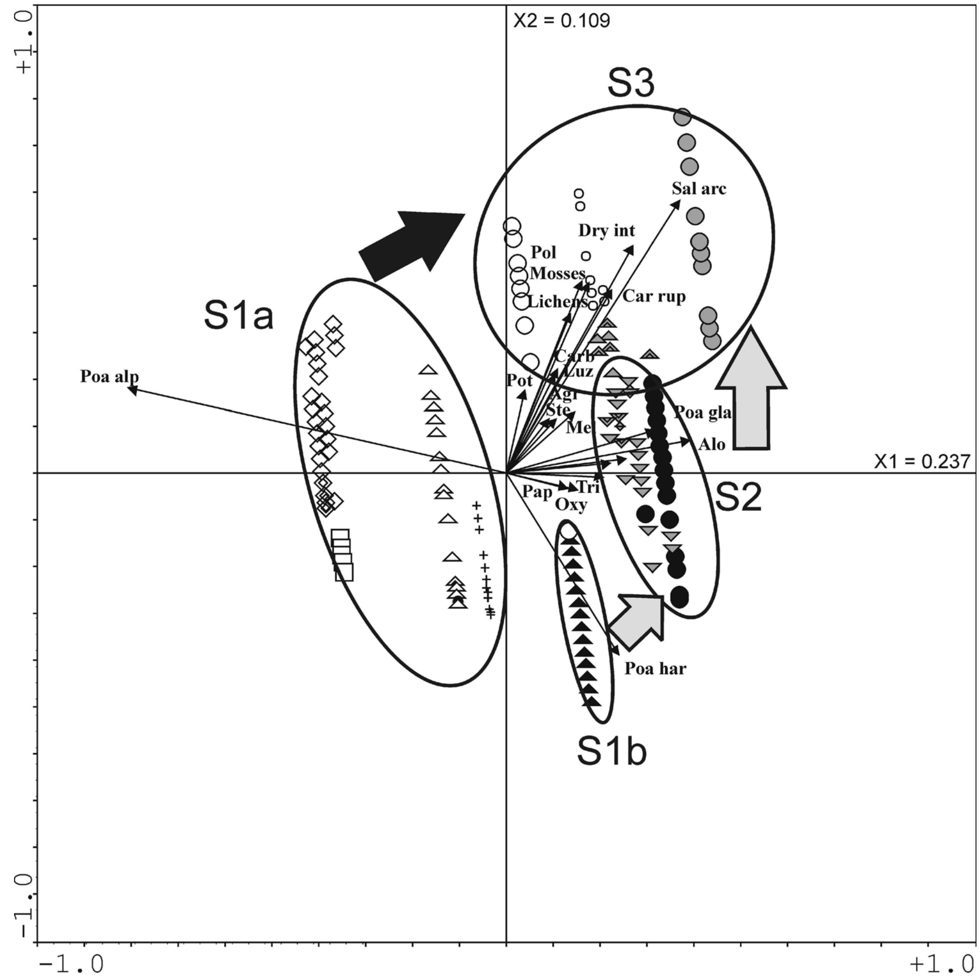

Figure 3. Multivariate analysis (RDA) of the vegetation surveys carried out in undisturbed conditions and within the nine landslides in the three study areas: BSC (black), BTC (white), HWC (gray), see also Table 2. Large circle, undisturbed sites; small circles, landslides older than 50 years (dating before 1950); square, 41–50 year old landslides (detached between 1950 and 1959); rhombus/diamond, 26–41 year old landslides (detached between 1959 and 1974); upward-pointing triangle, 13 years old landslides (detached in 1987); downward-pointing triangle, 12 year old landslides (detached in 1988); cross, 2–3 year old landslides (detached in 1997–1998); arrows, succession development; Agr, *Agropyron latiglume*; Alo, *Alopecurus alpinus*; Carb, *Carex bigelowii*; Car rup, *Carex rupestris*; Dry int, *Dryas integrifolia*; Luz, *Luzula confusa*; Mel, *Melandrium affine*; Oxy, *Oxyria digyna*; Pap, *Papaver radicatum*; Poa alp, *Poa alpigena*; Poa gla, *Poa glauca*; Poa har, *Poa hartzii*; Pol, *Polygonum viviparum*; Pot, *Potentilla pulchella*; Sal arc, *Salix arctica*; Ste, *Stellaria longipes*; Tri, *Trisetum spicatum*. See also Table 2.

Table 2) rather than to that in landslides of similar age at BTC (group S1a of Figure 3 and Table 2). However, within each of the identified groups (Figure 3 and Table 2), there are positive relationships between landslide age and both average total vegetation cover and complexity of floristic composition.

[23] A minimum of 13 years must elapse following landsliding before an enrichment in the floristic composition (rather than an increase in total cover) can be detected during vegetation succession and development.

3.3. Landslide Vegetation: Landscape Scale (BTC)

[24] BTC has the best-constrained range of landslide ages (Figure 4) and within this area the RDA separates the vegetation surveys at six landslides into five groups based on increasing time since landsliding (Figure 5 and Table 2). As expected, the increase in elapsed time since landsliding is associated with a shift from polar desert (pioneer stages of succession) to dwarf shrub tundra (more evolved stages of succession) over about 40 years. The first species to colonize is *Poa alpigena*, which attains an average cover of 23% in a relatively short time (2–3 years). Its cover increases progressively and dominates the pioneer and the early stages of the succession, at which time some early successional species begin to appear (e.g., *Alopecurus alpinus*, *Potentilla pulchella* var. *gracicaulis*, *Melandrium affine*). The oldest landslide (more than 50 years) showed the greatest vegetation cover and complexity and includes dwarf shrub com-

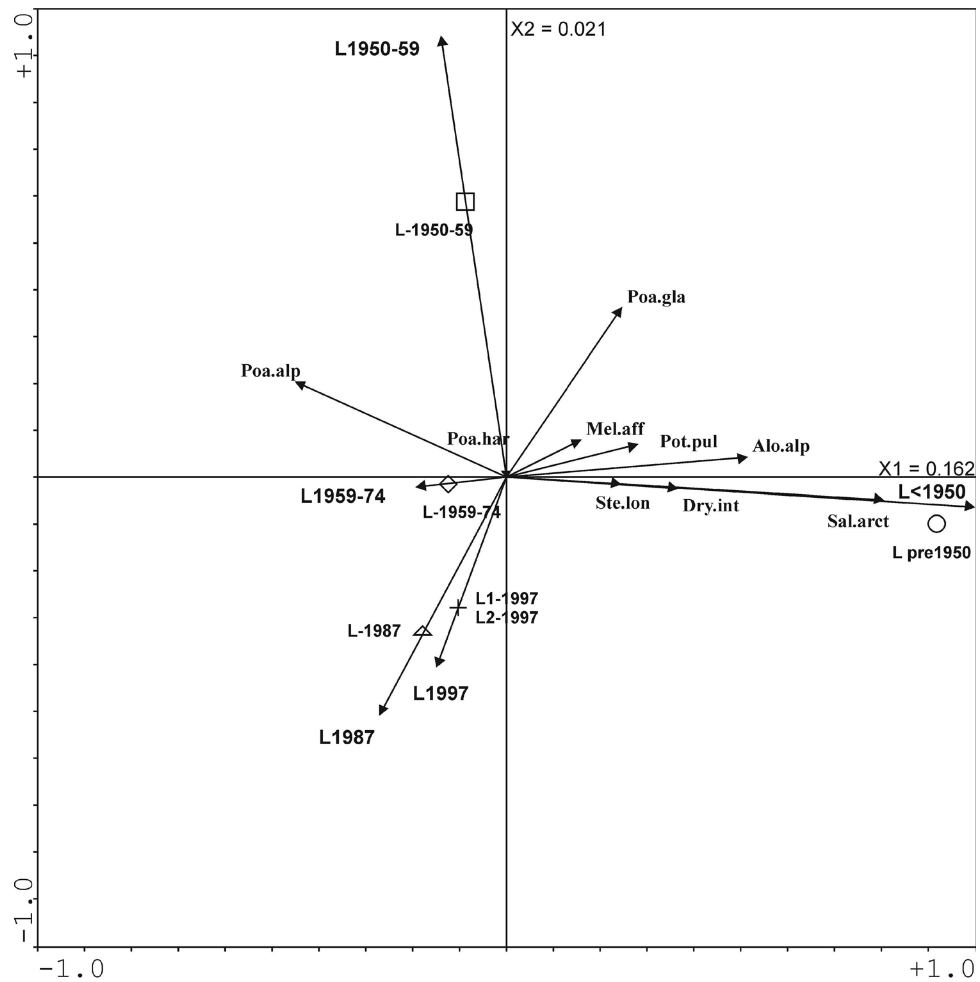

Figure 4. Multivariate analysis (RDA) of the vegetation surveys carried out within six landslides located at BTC. (For more details, see Table 2). Circles, landslides older than 50 years (dating before 1950); square, 41–50 year old landslides (detached between 1950 and 1959); rhombus/diamond, 26–41 year old landslides (detached between 1959 and 1974); upward-pointing triangle, 13 year old landslides (detached in 1987); cross, 3 year old landslides (detached in 1997); see Table 2. Alo alp, *Alopecurus alpinus*; Dry int, *Dryas integrifolia*; Mel aff, *Melandrium affine*; Poa alp, *Poa alpigena*; Poa gla, *Poa glauca*; Pot pul, *Potentilla pulchella*; Sal arc, *Salix arctica*; Ste lon, *Stellaria longipes*.

Figure 5. Vegetation colonization and coverage significantly changes from barren ground to almost continuous vegetation coverage comparing recent landslides (2–3 years old) in the scar zone and older landslides (more than 13 years old) in the toe zone at BTC.

munities dominated by *Salix arctica* var. *brownii* and the appearance of *Dryas integrifolia*.

4. Discussion

4.1. Vegetation on Undisturbed Terrain

[25] HWC has the most complex vegetation assemblage among the three study areas, dominantly exhibiting prostrate dwarf shrub tundra as well as a *Cassiope tetragona* community. Distance from relatively cold coastal waters, which may also be ice covered during parts of the growing season, is a significant factor affecting summer climate on the Fosheim Peninsula [*Lewkowicz*, 1990; *Atkinson*, 2000]. Automatic weather station records show that HWC (20 km from the head of Slidre Fiord) averages about 3°C warmer in July than Eureka, which is on the coast [*Alt et al.*, 2000]. Hourly measurements made using shielded Onset Hobo loggers in June and July 1994 show that air temperatures at Eureka (indicative of conditions in BTC) averaged 4.7°C, while they averaged 5.4°C at BSC and 7.4°C at HWC for the same period. The higher number of vascular plant species and the occurrence and abundance both of thermophilous species and of shrub communities at HWC are indicative of this difference. The relative paucity of species richness and the dominance of graminoid barrens at BTC (1–4 km from Slidre Fiord) relate to the colder conditions associated with incursions of coastal air, while those at BSC (12–15 km from Eureka Sound) are due to higher elevations. Even slight differences in summer climate appear to be important to vegetation given the extreme nature of the environment.

[26] Elevated salt contents in surface runoff from recent detachment slides and salt efflorescences are present on scar floors [*Kokelj and Lewkowicz*, 1999]. However, vegetation patterns did not reflect differing degrees of desalinization between and within landslides located above (BSC) and below the Holocene marine limit (BTC and HWC), unlike on the Yamal Peninsula, west Siberia [*Ukraintseva et al.*, 2003]. True halophytic species such as *Puccinellia phryganoides* and *Carex ursina* [*Dawson and Bliss*, 1987; *Bliss and Gold*, 1994] do not occur at BTC and HWC, and the slightly halophytic species *Potentilla pulchella* var. *gracicaulis* is homogeneously distributed in the three areas. The species that dominate vegetation communities at all three areas, *Alopecurus alpinus* and *Salix arctica*, have been described as characteristic of soils with relatively low salinity [*Dawson and Bliss*, 1987; *Bliss and Gold*, 1994]. These observations suggest that salt contents at the study areas are sufficiently low to limit true halophytes colonizers on both disturbed and undisturbed slopes.

4.2. Relation Between Landslide Age and Vegetation Development: Regional Scale

[27] On a regional scale, the study area location appears to be as important as landslide age in determining vegetation characteristics (Figure 2 and Table 2). This is evident when comparing the vegetation of the 13 year old landslides at HWC with that found at the two oldest landslides at BTC (>50 years and 45 years, respectively). Comparing the 12–13 year old landslides at HWC and BTC suggests that the warmer summer mesoclimate at HWC permits vegetation redevelopment at rates that are about four times faster than at BTC. However, within each area, there is a clear positive relation between landslide age and vegetation development (Table 2).

[28] These results indicate that where summer conditions are homogeneous, the relative age of landslides can be estimated by analyzing the type and the distribution of vegetation communities, their cover, and species richness. However, vegetation is not suitable as a landslide age indicator for this part of the Fosheim Peninsula as a whole due to the strong influence of mesoclimatic conditions (in particular, air temperature) on the rate of vegetation development. This confirms the high sensitivity of High Arctic vegetation to small differences in air temperature and is suggestive of the potential impacts of climate change [e.g., *Chapin et al.*, 2005], with special emphasis on the effects of summer warming on vegetation development. This could trigger a set of interlinked feedbacks that would amplify future rates of climate warming [e.g., *Chapin et al.*, 2005; *Euskirchen et al.*, 2007; *Schuur et al.*, 2007; *Lantz et al.*, 2009].

4.3. Relation Between Landslide Age and Vegetation Development: Landscape Scale

[29] On a landscape scale (i.e., at BTC), where climatic conditions can be assumed to be uniform, the average total vegetation cover and its floristic richness (i.e., number of vascular plant species) are generally proportional to the age of the landslides. The vegetation characteristics of the oldest failures become progressively more like those of adjacent undisturbed areas. Similar observations (but for Low Arctic vegetation) have been made for active-layer detachments on the Yamal Peninsula in western Siberia [*Ukraintseva et al.*, 2003]. Comparable results have also been obtained for landslides of different ages in geographical locations ranging from the tropical forests [*Dalling*, 1994] to the Caribbean [*Walker et al.*, 1996] to the Himalayas [*Reddy and Singh*, 1993].

[30] The time needed for vegetation restoration in this High Arctic environment appears slightly longer than elsewhere in the world. In the Caribbean, for example, communities similar to the mature tropical forest are reconstructed in 50 years [*Guariguata*, 1990; *Walker et al.*, 1996]. At BTC, more than 50 years are needed to restore vegetation patches with floristic composition similar to the more evolved communities occurring in undisturbed conditions.

4.4. Vegetation Colonization and Development/Successional Stages

[31] Vegetation colonization and succession show similar patterns among the three areas except where edaphic conditions linked to specific substrate characteristics dominate. Landslide colonization generally starts with *Poa alpigena*, which creates scattered populations at almost all the landslides examined (Table 2). Only where the substrate has specific characteristics does colonization start with other species such as *Poa hartzii* on clayey soils and *Poa glauca* on wind-exposed and rocky sites. *Poa alpigena* persists both as a dominant and codominant with *Alopecurus alpinus* in features of intermediate age. These species, favored by the harsh conditions induced by disturbance, have been previously described as early colonizers that restore vegetation in sites subject to both natural and anthropogenic

disturbance [*Babb and Bliss*, 1974]. Rapid reinvaders (i.e., efficient seed or bulbil producers such as grasses, *Polygonum viviparum*, *Saxifraga*, and *Draba* species) appear 2–3 years after landslide activation, but with sporadic occurrence and following stochastic mechanisms. Woody and semiwoody plants (*Salix arctica*, *Dryas integrifolia*) appear after 10–13 years, a time lag comparable to the 5–20 years described for other types of disturbance in the Arctic [*Babb and Bliss*, 1974].

[32] Similar patterns were observed by *Schuur et al.* [2007] who reported a shift from graminoid to shrub vegetation with thermokarst development. They also emphasized the importance of microclimatic and topographic conditions as key factors at the landscape scale.

[33] Unlike tropical regions [*Dalling*, 1994; *Walker et al.*, 1996], landslides in the High Arctic do not promote an increase in species diversity as almost all the species are recruited from adjacent stable slope segments. Moreover, pioneer and evolved communities in the study areas show similar floristic composition because of the ubiquitous nature of many vascular plants and their wide ecological tolerances and can be discriminated mainly by differences in relative species dominance [*Bliss and Svoboda*, 1984].

5. Conclusions and Implications

[34] Time since landsliding is the primary factor influencing vegetation colonization within active-layer detachments on the Fosheim Peninsula, Ellesmere Island. Colonization follows successional patterns, which require more than 50 years to redevelop a floristic composition similar to evolved communities. This elapsed time is still insufficient to rebuild the original vegetation cover and canopy/layering. The early and midcolonizers are typical of those previously described as being involved in the succession following both natural and anthropogenic disturbances in the High Arctic. These species show a high environmental flexibility and adaptability to a wide range of disturbance conditions with variable impacts and intensities.

[35] On a landscape scale, vegetation (type and distribution of vegetation communities, their coverage, and species richness) is a useful indicator of the relative age of landslides. On a regional scale on the Fosheim Peninsula, vegetation is not useful as a landslide age indicator due to the influence of mesoclimatic conditions on vegetation development. However, the apparently shorter time needed for landslide recovery in areas with warmer summer climate (e.g., HWC) suggests the high sensitivity of High Arctic vegetation to very small differences in growing season air temperatures, a factor that could trigger a set of interlinked feedbacks that would amplify future rates of climate warming.

[36] **Acknowledgments.** We are very grateful to Hugh French (University of Ottawa), Josef Svoboda (University of Toronto at Mississauga, Ontario), Norikazu Matsuoka (University of Tsukuba, Japan), and two anonymous reviewers who generously provided constructive comments on an earlier version of the paper. Financial support for field work was given by the Natural Sciences and Engineering Research Council of Canada. Logistical support was provided through the Antarctic Exchange Program of the Polar Continental Shelf Project, Energy Mines and Resources Canada (PCSP contribution 2210). Part of this work was supported by a grant from the Third University of Rome to Francesco Dramis and by PNRA (Progetto nazionale di Ricerche in Antartide).

References

Alt, B. T., C. L. Labine, D. E. Atkinson, A. N. Headley, and P. M. Wolfe (2000), Automatic weather station results from Fosheim Peninsula, Ellesmere Island, Nunavut, *Bull. Geol. Surv. Can.*, *529*, 37–97.

Atkinson, D. E. (2000), Modelling July mean temperatures on Fosheim Peninsula, Ellesmere Island, Nunavut, *Bull. Geol. Surv. Can.*, *529*, 99–111.

Babb, T. A., and L. C. Bliss (1974), Effects of physical disturbance on arctic vegetation in the Queen Elizabeth Islands, *J. Appl. Ecol.*, *11*, 549–562, doi:10.2307/2402208.

Bartleman, A. P., K. Miyanishi, C. R. Burn, and M. M. Côté (2001), Development of vegetation communities in a retrogressive thaw slump near Mayo, Yukon Territory: A 10-y assessment, *Arctic*, *54*, 149–156.

Batten, D. S., and J. Svoboda (1984), Plant communities on the uplands in the vicinity of the Alexandra Fiord Lowland, in *Ecology of a Polar Oasis, Alexandra Fiord, Ellesmere Island*, edited by J. Svoboda and B. Freedman, pp. 97–110, Captus Univ., Toronto, Ont, Canada.

Bell, T. (1996), The last glaciation and sea level history of Fosheim Peninsula, Ellesmere Island, *Can. J. Earth Sci.*, *33*, 1075–1086.

Bliss, L. C., and W. G. Gold (1994), The patterning of plant communities and edaphic factors along a high arctic coastline: Implications for succession, *Can. J. Bot.*, *72*, 1095–1107, doi:10.1139/b94-134.

Bliss, L. C., and J. Svoboda (1984), Plant communities and plant production in the western Queen Elizabeth Islands, *Holarctic Ecol.*, *7*, 325–344.

Bliss, L. C., J. Svoboda, and D. I. Bliss (1984), Polar deserts, their plant cover and plant production in the Canadian High Arctic, *Holarctic Ecol.*, *7*, 301–320.

Chapin, F. S., and C. Körner (Eds.) (1995), Arctic and alpine biodiversity: Patterns, causes and ecosystem consequences, in *Ecological Studies*, vol. 113, 323 pp., Springer, Heidelberg, Germany.

Chapin, F. S., et al. (2005), Role of land-surface changes in Arctic summer warming, *Science*, *310*, 657–660, doi:10.1126/science.1117368.

Dalling, J. W. (1994), Vegetation colonization of landslides in the Blue Mountains, Jamaica, *Biotropica*, *26*, 392–399, doi:10.2307/2389233.

Dawson, T. E., and L. C. Bliss (1987), Species patterns, edaphic characteristics, and plant water potential in a high-arctic brackish marsh, *Can. J. Bot.*, *65*, 863–868, doi:10.1139/b87-118.

Dyke, L. D. (2000), Stability of permafrost slope in the Mackenzie Valley, in *The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change*, edited by L. D. Dyke and G. R. Brooks, *Bull. Geol. Surv. Can.*, 547, 177–186.

Edlund, S. A., and B. T. Alt (1989), Regional congruence of vegetation and summer climate patterns in the Queen Elizabeth Islands, Northwest Territories, Canada, *Arctic*, *42*, 3–23.

Euskirchen, E. S., A. D. McGuire, and F. S. Chapin (2007), Energy feedbacks of northern high-latitude ecosystems to the climate system due to reduced snow cover during 20th century warming, *Global Change Biol.*, *13*, 2425–2438, doi:10.1111/j.1365-2486.2007.01450.x.

Geological Survey of Canada (1971), Geology of Slidre Fiord, District of Franklin, *Map 1928A*, scale 1:50.000, Geol. Surv. of Can., Ottawa.

Gould, W. A., D. A. Walker, M. Raynolds, H. Maier, S. Edlund, and S. Zoltai (2002), Canadian Arctic vegetation mapping, *Int. J. Remote Sens.*, *23*, 4597–4609, doi:10.1080/01431160110113962.

Gould, W. A., M. Raynolds, and D. A. Walker (2003), Vegetation, plant biomass, and net primary productivity patterns in the Canadian Arctic, *J. Geophys. Res.*, *108*(D2), 8167, doi:10.1029/2001JD000948.

Guariguata, M. R. (1990), Landslide disturbance and forest regeneration in the Upper Luquillo Mountains of Puerto Rico, *J. Ecol.*, *78*, 814–832, doi:10.2307/2260901.

Harris, C., and A. G. Lewkowicz (2000), An analysis of the stability of thawing slopes, Ellesmere Island, Nunavut, Canada, *Can. Geotech. J.*, *37*, 449–462, doi:10.1139/cgj-37-2-449.

Harris, S. A., and C. A. Gustafson (1993), Debris flow characteristics in an area of continuous permafrost, St. Elias Range, Yukon Territory, *Z. Geomorphol.*, *37*, 41–56.

Heginbottom, J. A., M. A. Dubreuil, and P. T. Harker (1995), Canada–Permafrost, Map 2.1, in *National Atlas of Canada*, 5th ed., Nat. Resour. Can, Ottawa.

Hernandez, H. (1973), Natural plant recolonization of surficial disturbances, Tuktoyaktuk Peninsula Region, Northwest Territories, *Can. J. Bot.*, *51*, 2177–2196, doi:10.1139/b73-280.

Intergovernmental Panel on Climate Change (IPCC) (2001), *Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, Cambridge.

Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis: Contribution of Working*

Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Summary for Policy Makers, edited by S. Solomon et al., Cambridge Univ. Press, New York.

Kokelj, S. V., and A. G. Lewkowicz (1999), Salinization of permafrost terrain due to natural geomorphic disturbance, Fosheim Peninsula, Ellesmere Island, *Arctic*, *52*, 372–385.

Lamoureux, S. F., and M. J. Lafrenière (2009), Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada, *Arct. Antarct. Alp. Res.*, *41*, 59–68, doi:10.1657/1523-0430-41.1.59.

Lantz, T. C., S. V. Kokelj, S. E. Gergel, and G. H. R. Henry (2009), Relative impacts of disturbance and temperature: Persistent changes in microenvironment and vegetation in retrogressive thaw slumps, *Global Change Biol.*, *15*, 1664–1675, doi:10.1111/j.1365-2486.2009.01917.x.

Leibman, M. O. (1995), Cryogenic landslides on the Yamal Peninsula, Russia: Preliminary observations, *Permafrost Periglacial Processes*, *6*, 259–264, doi:10.1002/ppp.3430060307.

Lewis, N. K. (1998), Landslide-driven distribution of aspen and steppe on Kathul Mountain, Alaska, *J. Arid Environ.*, *38*, 421–435, doi:10.1006/jare.1997.0335.

Lewkowicz, A. G. (1990), Morphology, frequency and magnitude of active-layer detachment slides, Fosheim Peninsula, Ellesmere Island, N.W.T. Permafrost—Canada, paper presented at Fifth Canadian Permafrost Conference, Univ. Laval, Québec City, Canada.

Lewkowicz, A. G. (1992), Factors influencing the distribution and initiation of active-layer detachment slides on Ellesmere Island, Arctic Canada, in *Periglacial Geomorphology*, edited by J. C. Dixon and A. D. Abrahams, pp. 223–250, John Wiley, Hoboken, New York.

Lewkowicz, A. G. (2007), Dynamics of active-layer detachment failures, Fosheim Peninsula, Ellesmere Island, Nunavut, Canada, *Permafrost Periglacial Processes*, *18*, 89–103, doi:10.1002/ppp.578.

Lewkowicz, A. G., and C. Harris (2005a), Frequency and magnitude of active-layer detachment failures in discontinuous and continuous permafrost, Northern Canada, *Permafrost Periglacial Processes*, *16*, 115–130, doi:10.1002/ppp.522.

Lewkowicz, A. G., and C. Harris (2005b), Morphology and geotechnique of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada, *Geomorphology*, *69*(1–4), 275–297, doi:10.1016/j.geomorph.2005.01.011.

Muc, M., B. Freedman, and J. Svoboda (1994), Vascular plant communities of a polar oasis at Alexandra Fiord, Ellesmere Island, in *Ecology of a Polar Oasis, Alexandra Fiord, Ellesmere Island*, edited by J. Svoboda and B. Freedman, pp. 53–63, Captus Univ. Publ., Toronto.

Nagamatsu, D., and O. Miura (1997), Soil disturbance regime in relation to micro-scale landforms and its effects on vegetation structure in a hilly area in Japan, *Plant Ecol.*, *133*, 191–200, doi:10.1023/A:1009743932202.

Porsild, A. E. (1957), *Illustrated flora of the Canadian Arctic Archipelago*, National Museum of Canada Bulletin 146, 209 pp., Dept. of North. Affairs and Natl. Resour, Ottawa, Ontario.

Porsild, A. E., and W. J. Cody (1980), *Vascular Plants of the Continental Northwest Territories, Canada*, 667 pp., Natl. Museums of Can, Ottawa, Ontario.

Reddy, V. S., and J. S. Singh (1993), Changes in vegetation and soil during succession following landslide disturbance in the Central Himalaya, *J. Environ. Manage.*, *39*, 235–250, doi:10.1006/jema.1993.1068.

Restrepo, C., et al. (2009), Landsliding and its multiscale influence on mountainscapes, *BioScience*, *59*(8), 685–698, doi:10.1525/bio.2009.59.8.10.

Schuur, E. A. G., K. G. Crummer, J. G. Vogel, and M. C. Mack (2007), Plant species composition and productivity following permafrost thaw and thermokarst in Alaskan tundra, *Ecosystems (N. Y.)*, *10*, 280–292, doi:10.1007/s10021-007-9024-0.

Ter Braak, C. J. F., and P. Šmilauer (1998), *CANOCO Reference Manual and User's Guide to CANOCO for Windows: Software for Canonical Community Ordination (version 4)*, 351 pp., Centre for Biometry, Wageningen, Netherlands.

Trivedi, M. R., P. M. Berry, M. D. Morecroft, and T. P. Dawson (2008), Spatial scale affects bioclimate model projections of climate change impacts on mountain plants, *Global Change Biol.*, *14*, 1089–1103, doi:10.1111/j.1365-2486.2008.01553.x.

Ukraintseva, N. G., I. D. Streletskaya, K. A. Ermokhina, and S. Y. Yermakov (2003), Geochemical properties of plant-soil-permafrost systems on landslide slopes, Yamal, Russia, paper presented at Eighth International Conference on Permafrost, Int. Permafrost Assoc., Zurich, Switzerland, 21–25 Jul.

Walker, D. A., and M. D. Walker (1991), History and pattern on disturbance in Alaskan Arctic terrestrial ecosystems: A hierarchical approach to analysing landscape change, *J. Appl. Ecol.*, *28*, 244–276, doi:10.2307/2404128.

Walker, L. R., D. J. Zarin, N. Fetcher, R. W. Myster, and A. H. Johnson (1996), Ecosystem development and plant succession on landslides in the Caribbean, *Biotropica*, *28*, 566–576, doi:10.2307/2389097.

N. Cannone, Department of Chemical and Environmental Sciences, University of Insubria, Via Lucini 3, I-22100 Como, Italy. (nicoletta.cannone@uninsubria.it)

M. Guglielmin, DBSF, University of Insubria, Via Dunant 3, I-21100 Varese, Italy.

A. G. Lewkowicz, Department of Geography, University of Ottawa, Ottawa, ON K1N 6N5, Canada.