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Vegetation-Banked Terraces on Subantarctic Macquarie Island: a Reappraisal

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Abstract

Vegetation-banked terraces with alternating bands of vegetation and gravel are spectacularly developed on the plateau of subantarctic Macquarie Island. Previous work has described two distinct, apparently unrelated types of vegetation-banked terraces on the island, ''windward'' and ''leeward,'' depending on their exposure to the prevailing westerly winds. Here we have documented aspects of terrace morphology and vegetation. The terraces are dynamic, with mobile gravel, substrate erosion, and vegetation growth all in evidence. By focusing on the processes occurring, we conclude that the ''windward'' and ''leeward'' types are actually two related forms that grade from one into the other, depending on hillside aspect. In addition, we describe stone-banked terraces, not previously reported from Macquarie Island. Recent changes on the island resulting in widespread death of the cushion plant *Azorella macquariensis* may impact on the maintenance of terrace stability in the long term.

Introduction

Patterning of vegetation and ground occurs in a range of climates from hot arid (Rózycki, 1986; Eddy et al., 1999) to polar (Selby, 1971). It is widespread in alpine (Jahn, 1958; Hansen-Bristow and Price, 1985; Lynch and Kirkpatrick, 1995; Mark et al., 2001; Butler et al., 2004), Arctic tundra (Harris, 1982; Douglas and Harrison, 1996), and subantarctic environments (Taylor, 1955; Hall, 1983; Haussmann et al., 2009b). Terracing is a form of patterning resulting from the restriction of movement of material down a slope (Warren Wilson, 1952). The downslope movement results from instability where the ground is not vegetated, or is vegetated but is capable of being disturbed by geomorphic processes or bioturbation. Uneven movement and retention of the mobile surface mantle results from irregularities on the slope that locally impede downslope movement. If damming is caused mainly by vegetation, then a vegetation-banked form results; if stones cause damming, then a stone-banked form results.

We have seen vegetation-banked terraces in a variety of Southern Hemisphere locations: in temperate areas (alpine Snowy Mountains in Australia), cool temperate areas (southern Chile; Stewart Island, New Zealand), and subantarctic areas (Heard Island, Îles Kerguelen, Macquarie Island). They are spectacularly developed on Macquarie Island, and we present here a reappraisal of their described forms from this location.

Subantarctic Macquarie Island, at 54°30′S, 158°55′E, is small (12,785 ha), elongate (34 km long, up to 5 km wide), with an undulating plateau 150–300 m a.s.l., whose highest point is Mount Hamilton, at 433 m (Fig. 1). The climate is oceanic cloudy, cool, wet, and windy. Recorded at the meteorological station at 6 m a.s.l., the mean number of cloudy days per year is 289, the mean air temperature of the coolest month is 3 °C, mean air temperature of the warmest month is 7 °C, and the mean annual precipitation is 968 mm. The annual average wind speed recorded at 9 a.m. is 9.6 m s^{-1} and at 3 p.m. is 9.75 m s^{-1}. Winds stronger than 5.5 m s^{-1} are overwhelmingly from the west and northwest (Bureau of Meteorology, 2012).

Previous work has described two distinct, apparently unrelated types of vegetation-banked terraces on Macquarie Island dependant on their exposure to the prevailing westerly winds: ''leeward terraces'' on east-facing slopes and ''windward terraces'' on west-facing slopes (Taylor, 1955; Ashton and Gill, 1965; Löffler et al., 1983; Selkirk et al., 1988; Selkirk, 1998). The terraces have alternating bands of vegetation and surfaces of bare soil and gravel (Fig. 2). Unvegetated chutes connect one bare band to the next downslope. ''Leeward terraces'' form extensive flights often covering whole hill- and mountainsides (Fig. 2, parts a and b) on the plateau above about 200 m a.s.l. (Fig. 1). They are widespread in areas of feldmark (discontinuous short herb vegetation dominated by *Azorella macquariensis* and bryophytes), and occur less commonly in areas of discontinuous short herb vegetation dominated by *Festuca contracta*, *Luzula crinita,* and *Agrostis magellanica* (Selkirk et al., 1988; Selkirk and Adamson, 1998). ''Windward terraces'' (Fig. 2, parts c and d) occur on west-facing slopes in similar vegetation communities and at similar altitudes.

Our examination of the role of wind in the maintenance and formation of these vegetation-banked terraces has led us to a new model of terrace morphology on the island. In addition, we describe stone-banked terraces, previously unknown from Macquarie Island. Recent changes on the island resulting in widespread death of *Azorella macquariensis* on the plateau may impact on the maintenance of terrace stability in the long term.

Methods

Extensive observations and measurements of terrace attributes including aspect, slope, dimensions, vegetation species, as well as wind velocity measurements were made during summer fieldtrips to Macquarie Island between 1979–1980 and 1994–1995. Table 1 shows attributes recorded for a sample of 35 terrace sites during the summer of 1986–1987, and Table 2 shows the species recorded at seven plateau feldmark sites during a vegetation survey in
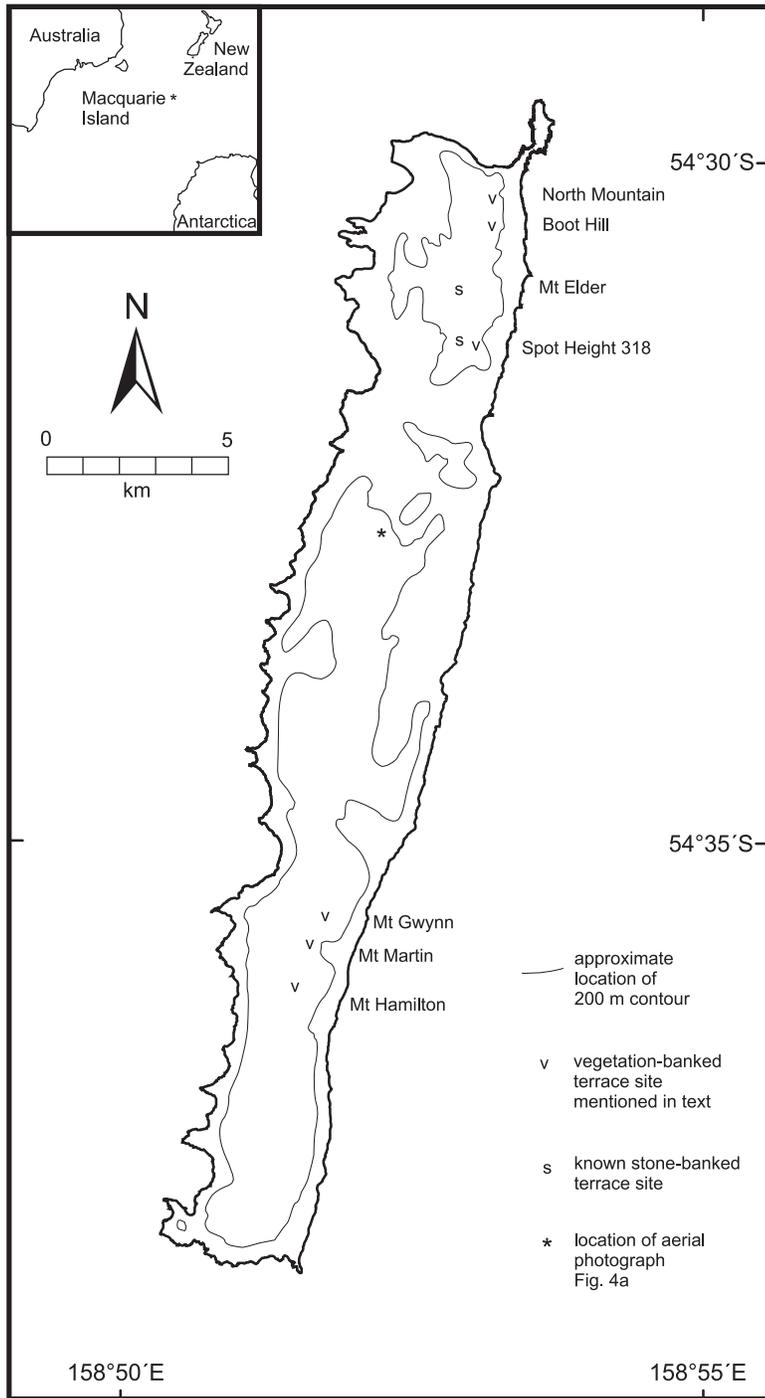
FIGURE 1. Macquarie Island showing location of terrace sites mentioned in the text and the approximate location of the 200 m contour.

1979–1980. Species of first contact were recorded at 1-cm intervals along 20-m transects across terraces.

In 1993 and 1994, wind velocity was measured across terrace profiles on east-facing slopes at Mount Martin, Spot Height 318, and Boot Hill, and on west-facing slopes at Mount Gwynn and North Mountain (Fig. 1). Measurements were made approximately 0.05 m above the surface, using a handheld Deuta Anemo cup anemometer with visual readout. It could be read to 0.5 m s^{-1} and the anemometer was operated upside down, taking care that the operator was downwind. Measurements were

recorded as a velocity range (for example, 3–5 m s^{-1}) over a 10-s time period, and the strongest gust during that time was also recorded. The number of measurements taken at each position varied due to field constraints. All measurements were taken when the average wind velocity 1 m above the average slope of the surface was 9.0 ± 1.0 m s^{-1}.

Aerial photographs, including stereo pairs, from the Commonwealth of Australia series CAS 8467 of 1976 were examined to supplement field observations. All these data sources were analyzed, and factors influencing terrace form were then evaluated.
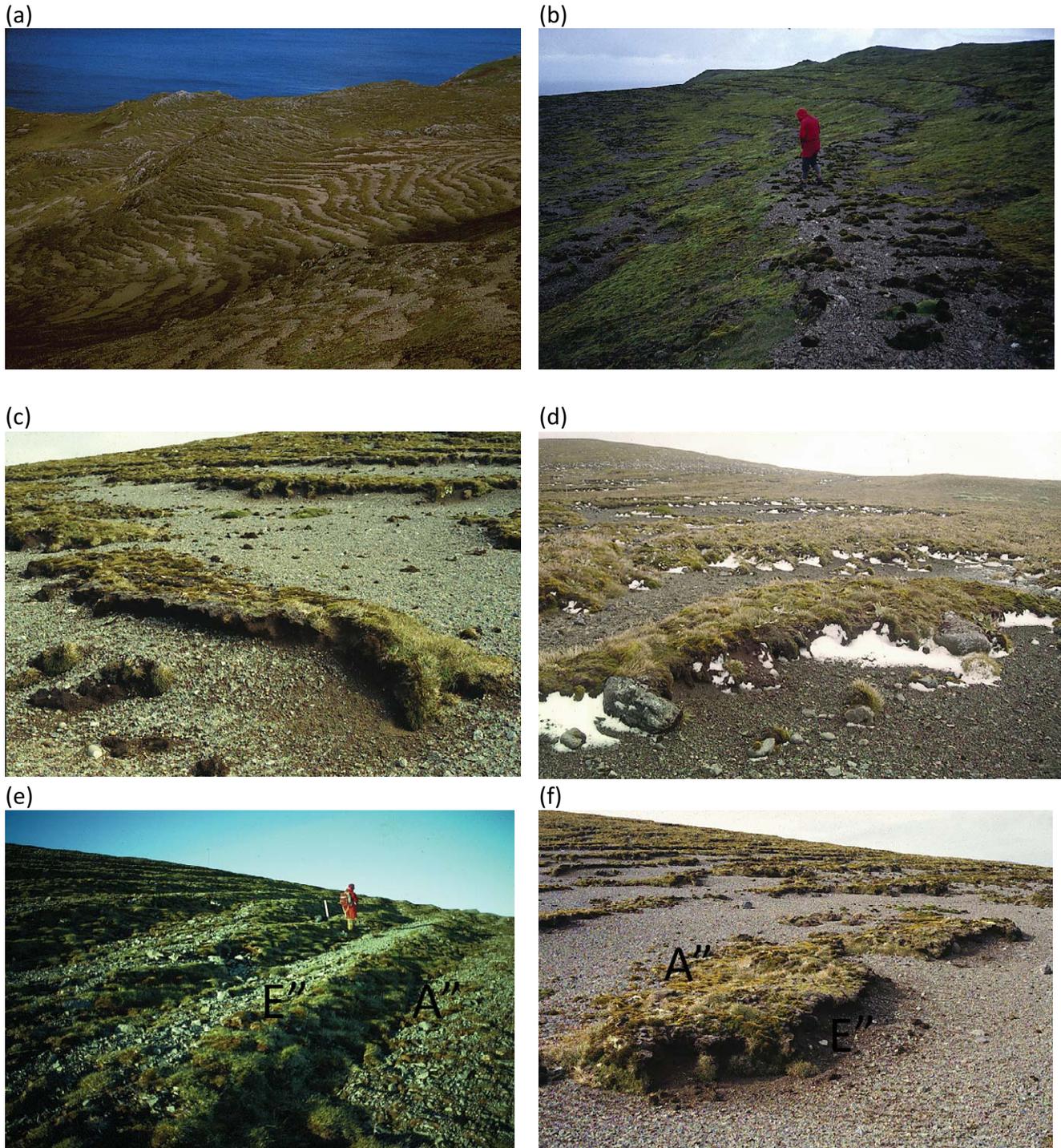
FIGURE 2. (a) Vegetation-banked terraces form flights across hillslopes, looking along the east-facing slopes of Mount Gwynn. (b) Vegetation-banked terrace morphology on an east-facing slope. (c) Vegetation-banked terrace morphology on a west-facing slope. (d) Vegetation-banked terraces on a west-facing slope showing snow and ice accumulation at cliffed downslope edge of each terrace. (e) Vegetation-banked terraces tilting down to the west on a south-facing slope. (f) Example of erosion and vegetation damage (E″) and accretion and potential vegetation growth (A″) on vegetation-banked terraces on west-facing slope. Prevailing wind is from the bottom right hand corner of photograph.

TABLE 1

Attributes measured at terrace sites on the plateau of Macquarie Island in 1986–1987. Zero value is shown as 0, empty cell means data not collected. * refers to notes in that row. Key to plant species names—angiosperms: *1 = Acaena minor, 2 = Agrostis magellanica, 3 = Azorella macquariensis, 4 = Epilobium spp., 5 = Festuca contracta, 6 = Luzula crinita, 7 = Pleurophyllum hookeri, 8 = Ranunculus crassipes, 9 = Stilbocarpa polaris*; pteridophyte: *10 = Grammitis poeppigeana*; bryophytes: *11 = Andreaea spp., 12 = Racomitrium crispulum, 13 = Breutelia pendula, 14 = Dicranoloma billardierei, 15 = Ditrichum strictum*, usually as polsters, *16 = Jamesoniella colorata, 17 = Polytrichastrum alpinum*; lichens: *18 = Usnea and Cladonia spp.*

Sector	Site Number	Site Aspect (°)	Hillslope (°)	Riser Slope (°)	Riser Width (m)	Riser Vegetation	Terrace Length (m)	Tread Slope (°) Along/Down Towards	Tread Width (m)	Tread Vegetation	Notes
N	5	10	22	50	0.6	2,3,6,10,12		20–25	1		*sorted polygons ~0.2 m diameter on treads, fines in center, mosses on larger stones.
N	8	15	12	15	5–6	2,3,7,18		0	*4	*11,12	
N	16	15	15	25	1–2	2,3,12,15	to 20	10/NW	1–1.5	3,12,15	
N	20	05	10	20	2–3	1,2,3,6,11,12,14,15,17	50+	3/W	3–4	11,12,15	*riser veg. mostly *Agrostis.*
N	44	10	17	23–25	2–4	*1,2,5,6,12	20–40	10/W	2–3	11,12,15	
N	10	35	15	20–22	5–7	2,3,4,6,7,13,14		1–2	3–4	2,3,11,12,15,17	
N	23	30	15	20	1–1.5	1,2,3,7,9,12,16	25–30	4/W	*0.8–1		*larger gravel at outer edge of tread.
N	34	335	10	12	0.5–1	1,2,3,12	5–10	6	1–3	*2,12,18	*tread veg. very sparse.
E	1	55	5–15	10–15	3–4	1,2,3,6,12,18			*5–10	11,12,15	*treads narrow to 3–4 m uphill as hillslope steepens.
E	15	60	13	25	1.5–2	*1,2,3, 6,7,9,12,17	40+	0	1.5–3	12,15	*riser veg. mostly *Azorella.*
E	17	80	21	30–40	1–4	*2,3,12,15	4–20	to 10	1–2	*15	*riser veg. 90% *Azorella*; tread veg. occasional polsters; interconnecting terraces with active chutes.
E	21	60	11	18–20	2–2.5	2,3,6,12,17	20–30	3/N	1–2	3,12	*larger gravel at outer 0.4 m of tread.
E	30	55	8–12	20–25		*1,2,3,6,8,12,13,14,17	20–50	0	2–2.5	*1,2,3,6,8,12,13,14,17	*completely vegetated terraces; riser and tread veg. same; *Azorella* 50% cover, minor spp. in equal amounts.
E	37	50	19	20–50*	1.5–3	*2,3,6,7,12	10–20	7/NW	1–2.5	15	*risers convex in places; *Azorella* and *Pleurophyllum* most abundant spp.
E	38	50	23	25–90 (av. 60)	1–3	*2,3,6,7,12	20	14/NW	0.5–1	15	*Azorella* and *Pleurophyllum* most abundant spp.
E	4	95	13–14	15–25	1–4	1,2,3,6,12		0–5	2.5–3	15	
E	6	90	18	25	1–4 (av. 2)	1,2,3,6,12,17		5–15	*1.5–3	1,2,12,15	*frost stripes on gravel of treads.
E	11	105	14	25–30	4	*1,2,3,6,7,10,12		4/S	2–3	*11,2,6,15	*little *Azorella* on risers; 20–30% veg. cover on treads.
E	18	105	4	5–10	1–1.5	2,3,6,12,15	2–50	3	2–4	*8,11,15,17	*tread veg. very sparse.
E	19	95	15	20	1.5	*3,11,12,15	50+	0–3/N	1	*11,12,15	*riser veg. is *Azorella* patches 0.5–1 m diam. with bryophytes in stripes that extend onto tread below; few plants on treads.
E	22	100	22	25	1–2	5	20	5–10	0.5–1		
E	28	60	24	20–30	1–3	2,3,6,12	30–50	15	3–4.5	*	*larger gravel sorted to outer edge.

264 / Arctic, Antarctic, and Alpine Research

TABLE 1 (Cont.)

Sector	Site Number	Site Aspect (°)	Hillslope (°)	Riser Slope (°)	Riser Width (m)	Riser Vegetation	Terrace Length (m)	Tread Slope (°) Along/Down Towards	Tread Width (m)	Tread Vegetation	Notes
E	35	60	10	15–18	2–6	*2,3,5,6	to 40	2/N	4–6*	11,15	*riser veg. mostly Agrostis and Luzula; frost action evident.
E	24	115	16	25	2–4	*1,2,3,6,10,12,17	50+	0	1.5	*	*on risers Azorella 85% cover and lower edge has moss skirt extending onto treads; larger gravel sorted to front edge of treads.
E	29	115	13	25	4	*3,6,12	50+	4/S	3	11,12,15	*on risers Azorella 85% cover, at base moss skirt extends onto treads; scattered Andreaea and Ditrichum polsters + Racomitrium stripes to 15% cover on treads.
S	31	155	17	30–35	2–5	*2,3,6,7,8,17	15–50	1/W	1–3	*2,3,6,7,8,17	*Azorella 80% cover on riser, 50% of tread veg. Tread veg. almost complete cover, only 0–5% mobile gravel.
S	36	135	18	20	1–2.5	*1,2,3,6,12	20–30	13/SW	1.5–2.5	*3,11,12,15	*tread veg. includes 0.1 m clumps of Azorella; tread convex in outer half curving over to top edge of riser veg. *Azorella 10%, Agrostis 40%, bryophytes 30% in riser veg.
S	41	140	12–13	35	1–1.5	*1,2,3,6,11,12,16,17	50	3	1–3	*2,11,12,15	*Agrostis clumps in tread veg. Gravel spills from one terrace to next stable one down.
S	14	180	13	20	1.5–2	*1,2,3,6,8,12,18	20+	15/W	10		*Azorella, Racomitrium each close to 50% cover in risers; frost stripes on treads bear 183°.
S	32	180	18–21	35	1.5–2.5	*3,6,12,18	3–20	11	0.5–3	*12,15	*riser veg. predominantly Azorella; tread veg. very sparse; 25° slope on chutes.
S	40	185	18	25	1.5–3	*1,2,3,6,7	5–30	12/SW	4	*11,12,15	*riser veg. <10% Azorella; tread veg. <10% cover; outer edge of treads dribble over into 20° chutes.
W	26	250	3.5	*5–10	*2.5–3	*11,15	30	*4/S	*1.5–2	*2,3,6,12	*riser is gravel; tread is vegetation, 50% Azorella.
W	27	285	6	*5–10	*1–2	*	10–15	*0	*1–1.5	*3,6,12,17,18	*riser is gravel; tread is vegetation.
W	33	310	30–35	45	0.5–1.5	*2,3,12,18	2–6	25	2–4	*12	*risers irregular patches (0.5–1.5 × 2–6 m) of veg., Azorella at top with some Agrostis, Racomitrium, lichens; some gravel overriding veg. at top; lower edge of veg. eroded.
W	39	300	17	15–40	0.5–1.5	*3,12	20+	13–15/W	2–5		*riser veg. is lines of Azorella patches 0.05–1.5 m diameter, each patch wind-eroded at lower i.e. W edge; gravel moving actively downhill and scattered on veg.; frost heaving obvious.

J. M. SELKIRK-BELL AND P. M. SELKIRK / 265

TABLE 2

Plant species recorded in transects across feldmark terraces on the plateau of Macquarie Island in 1980.

Vascular plants*	Bryophytes**	Lichens***
Acaena minor (Hook.f.) Allan	*Andreaea* spp.	*Buellia* sp.
Agrostis magellanica Lam.	*Bartramia ithyphylla* Brid.	*Cetraria* sp.
Azorella macquariensis Orchard	*Breutelia pendula* (Smith) Mitt.	*Cladia aggregate* (Sw.) Nyl.
Cardamine corymbosa Hook.f.	*Chiloscyphus bispinosus* (Hook.f. & Taylor) J.J.Engel & R.M.Schust.‡‡	*Cladonia* sp.
Colobanthus quitensis (Labill.) Druce	*Conostomum pentastichum* (Brid.) Lindb.	*Hypogymnia lugubris* (Pers.) Krog
Coprosma perpusilla Colenso	*Cryptochila grandiflora* (Lindenb. & Gottsche) Grolle ‡‡	lichen, 2 unidentified genera
Epilobium brunnescens (Cockayne) P.H.Raven & Engelhorn	*Dicranoloma billardierei* (Brid.) Paris	*Pertusaria* sp.
Epilobium pedunculare A. Cunn.	*Ditrichum punctulatum* Mitten	*Pseudocyphellaria glabra* (J.D.Hook. and Taylor) Dodge
Festuca contracta Kirk	*Ditrichum strictum* (Hook.f. & Wilson) Hampe	*Stereocaulon* sp.
Grammitis poeppigiana (Mett.) Pic.-Serm.	hepatic, 2 unidentified genera	*Stereocaulon argus* J.D.Hook. and Taylor
Luzula crinita Hook.f.	*Hymenoloma antarcticum* (Mull.Hal.) Ochyra‡	*Stereocaulon ramulosum* (Sw.) Räuschel
Pleurophyllum hookeri Buchan.	*Hypnum cupressiforme* Hedw.	*Usnea* sp.
Poa annua L.	*Jamesoniella colorata* (Lehm.) Spruce ex Schiffn.‡‡	
Ranunculus crassipes Hook.f.	*Lepidolaena sp.*	
Stilbocarpa polaris (Hombr. & Jacquinot ex Hook.f.) A.Gray	*Lepidozia sp.*	
Uncinia hookeri Boott in J.D.Hooker	*Leptostomum inclinans* R.Br.bis.	
	Metzgeria sp.	
	Notoligotrichum australe (Hook.f. & Wilson) G.L.Sm.	
	Plagiochila retrospectans (Nees) Nees†	
	Polytrichastrum alpinum (Hedw.) G.L.Sm.	
	Ptychomnion densifolium (Brid.) A.Jaeger	
	Racomitrium crispulum (Hook.f. & Wilson) Hook.f. & Wilson	
	Racomitrium pruinosum (Wilson) Müll.Hal.	
	Rhacocarpus purpurascens (Brid.) Paris	
	Riccardia cochleata (Hook.f. & Taylor) Kuntze‡‡	
	Sanionia uncinata (Hedw.) Loeske	
	Thuidiopsis furfurosa (Hook.f. & Wilson) M.Fleisch.	
		TOTAL OF 55 SPECIES

*Authorities for vascular plants follow George et al. (1993); **authorities for mosses follow Seppelt (2004) unless otherwise marked; ***authorities for lichens follow Kantvilas and Seppelt (1992); ‡authority follows Ochyra and Broughton (2004); ‡‡authorities follow McCarthy (2003); †authority follows Inoue and Seppelt (1985).

Results

TERRACE ATTRIBUTES

In Table 1, the terrace sites have been grouped into four sectors according to hillslope aspect: north-facing (315–44°), east-facing (45–134°), south-facing (135–224°), west-facing (225–314°). The data clearly illustrate the descriptions previously made of vegetation-banked terracing on the plateau of Macquarie Island (Taylor, 1955; Ashton and Gill, 1965; Löffler et al., 1983; Selkirk et al., 1988; Selkirk, 1998).

In summary, terraces generally are long, some exceeding 50 m in length, and roughly parallel to contours. There is considerable variation in all terrace dimensions. There is a marked difference in terrace form between locations on west-facing slopes (e.g. Table 1: Sites 26 and 27) where gravel is on risers sloping more steeply than the overall hillslope (Taylor's 1955 windward terraces) and sites with all other aspects where vegetation is on risers sloping more steeply than the overall hillslope (Taylor's 1955 leeward terraces). While riser vegetation is most commonly dominated by *Azorella macquariensis* (e.g. Table 1: Sites 15, 17, 24), many other species grow at terraced sites (Tables 1 and 2). At some sites *A. macquariensis* is a minor component of riser vegetation (e.g. Table 1: Sites 11, 41) or is absent (e.g. Table 1: Site 44). Evidence of mobile gravel was seen at many sites (e.g. sorted polygons at Table

1: Site 8, frost stripes in gravel at Site 6, gravel spills at Site 41, gravel chutes at Site 32). At some sites vegetation is complete on treads as well as risers, holding gravel stable (e.g. Table 1: Sites 30, 31).

Terraces on east-facing slopes (Taylor's leeward form) have distinct patterns of treads and risers (Fig. 2, part b) that approximately parallel the contours. The terraces occur on hillslopes of between 4° and 35°, are most pronounced on slopes greater than 10°, and tilt from the horizontal on hillslopes above about 11° (Table 1).The risers are steep (5–90°) and generally between 0.5–6 m high, while the treads have a more gentle slope (0–10°), and are between 1 and 10 m wide (Table 1).

The terraces on west-facing hillsides on slopes up to 10° (Taylor's windward form) (Table 1: Sites 26, 27) are strikingly different in form to those described above. The vegetated strip is essentially horizontal, up to 5 m long (across slope), and 2 m wide (up and downslope). The west-facing edge of the vegetated strip is an eroding face of vegetation and soil material 0.1–0.3 m high (Fig. 2, part c). The graveled area of the terrace has a slope that is similar to that of the hillside, and tends not to be sorted to the same degree as the gravel tread of the terraces on east-facing slopes. West-facing slopes steeper than 15° do not support a regular terraced pattern, but have unconnected oval-shaped patches of vegetation widely spaced on the slope (Table 1: Sites 33, 39).

Where hillslopes face northwards or southwards, terraces do not parallel the contour but tilt down to the west (Fig. 2, part e), although they retain the stepped profile found on east-facing slopes, with vegetated risers and graveled tread.

WIND

Table 3 shows average wind velocity measurements recorded at various locations on the terrace profile. These numbered positions are located on the cross sections (Fig. 3), with the east-facing sites shown in Figure 3, part a, and the west-facing sites in Figure 3, part b. The mean velocity measured over the east-facing sites was 2.7 ± 0.1 m s^{-1}, and over the west-facing sites was 3.5 ± 0.1 m s^{-1}.

At the east-facing sites there were statistically significant (ANOVA: $p < 0.0001$) velocity differences at various positions on the terrace profile. The base and center of the vegetated riser

(positions 1 and 2) were more protected from wind than the outer edge of the tread (position 4) and the top of the riser (position 3), where vegetation damage and soil scour by wind-driven rain and ice were observed. The calmer areas below the top of the riser and at its base are sites of vegetation protection and snow accumulation during periods of strong wind.

The west-facing sites show smaller but also statistically significant differences (ANOVA: $p < 0.001$) in wind speed across the terrace profiles. The graveled area at the base of the cliffed vegetation edge (position 4) is the most exposed, whilst the junction zone between the upslope edge of the vegetation and the downslope edge of the gravel (positions 1 and 6) is least exposed. Again, at the most exposed position, active erosion and vegetation damage are occurring, demonstrated by exposed plant roots, damaged shoots, and soil collapse. At the least exposed position (position 1), vegetation growth and mineral material deposition from slope wash are occurring. The plants were commonly growing into the mineral material and so are spreading upslope.

Needle ice that forms in the bare soil of the terrace treads on both east-facing and west-facing slopes churns mineral particles that are then moved by wind and lodge in the vegetation where wind velocity is lowest. Stones up to 0.05 m diameter have been observed blown from bare areas onto the surface of foliage. Sand and ice (hail) blown by strong wind abrade the vegetation of the terraces. With terraces on east-facing slopes, the main impact area of this blast is the upslope edge of the vegetated riser. Here, it is common to see damaged leaves and bare stems where ice, sand, and larger particles have blasted the plants. On west-facing slopes the impacts of the mineral particles, ice, snow, and rain are more severe than on east-facing slopes and are concentrated at the steep downslope edge of the vegetation (Fig. 2, part d). The impact of rain and ice blown nearly horizontally in strong winds also scours soil material on the bare treads of all terrace styles on Macquarie Island.

AERIAL PHOTOGRAPH INTERPRETATION

Figure 4, part a, is an aerial photograph of a dome-shaped hill showing the location of leeward and windward terraces, *sensu* Taylor (1955). The banding of the contour-parallel terraces on east-facing slopes is clearly seen to the right, with the more diffuse pattern of

TABLE 3

Wind velocity measurements (m s^{-1}) on terraces on east-facing and west-facing slopes at numbered positions shown on Figure 3. Velocities are means $\pm$ s.d.

Position as shown on Figure 3	East-facing slopes			West-facing slopes		
	wind velocity (m s^{-1})		n	wind velocity (m s^{-1})		n
1 – downwind edge of vegetation band	2.3 ± 1.2		119	3.0 ± 1.2	calmest	110
2 – mid vegetation band	2.9 ± 1.3		50	3.6 ± 1.4		110
3 – upwind edge of vegetation band	3.9 ± 1.4	windiest	119	3.3 ± 1.0		110
4 – downwind edge of gravel band	3.5 ± 1.3		119	3.9 ± 1.1	windiest	110
5 – mid gravel band	1.7 ± 1.1	calmest	99	3.6 ± 1.4		110
6 – upwind edge of gravel band	1.7 ± 0.9	calmest	99	3.5 ± 1.5		110

J. M. Selkirk-Bell and P. M. Selkirk / 267

(a)

(b)
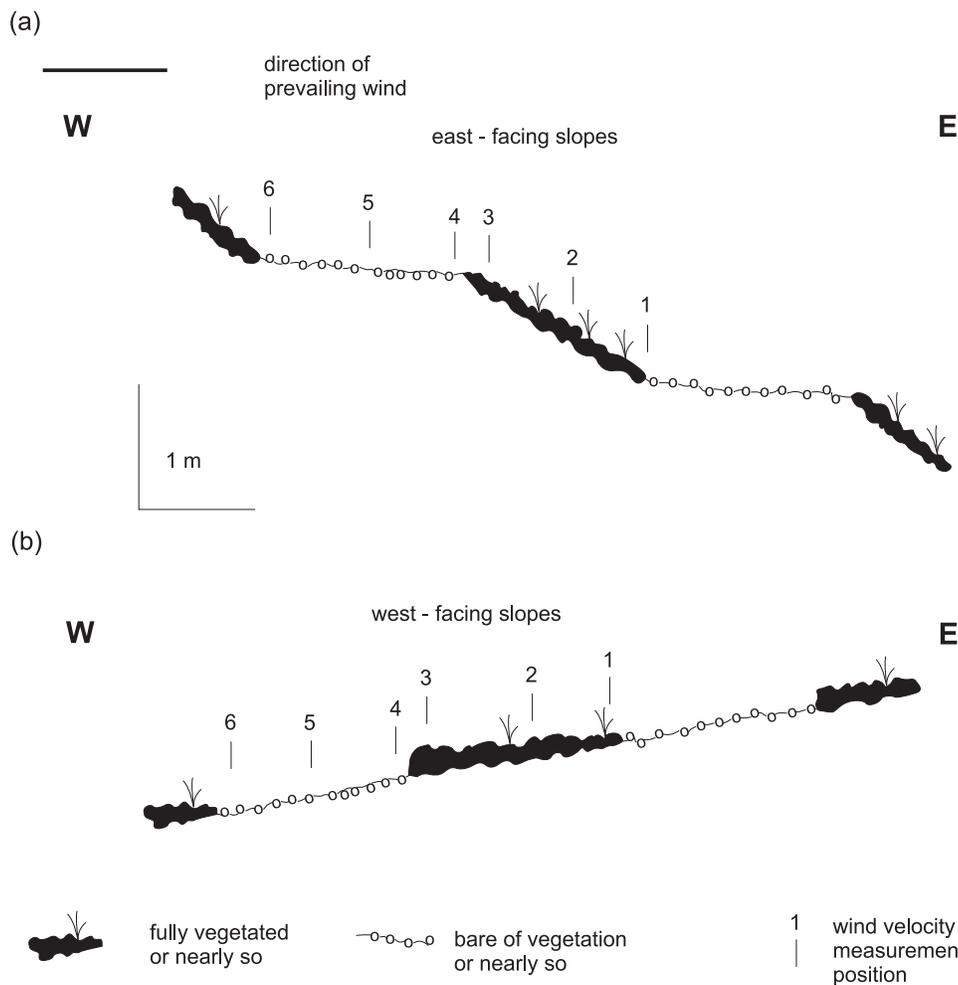
FIGURE 3. Wind velocity measurement positions on terraces on (a) east-facing and (b) west-facing slopes.

the terraces on west-facing slopes to the left. The situation shown in Figure 4, part a, is shown schematically in Figure 4, part b. In Figure 4, part b, the contour-parallel terraces found on west-facing slopes between 5° and 15° occur at position A. These are the windward terraces of Taylor (1955) and are illustrated in Figure 2, parts c and d. Position B shows the location of the contour-parallel terraces occurring on east-facing slopes described as leeward terraces by Taylor (1955), and discussed by Löffler et al. (1983) and Selkirk et al. (1988) (Fig. 2, parts a and b). C and D represent positions where the east-facing style terraces occur on slopes facing north and south and where these terraces tilt down to the west from the horizontal, regardless of the slope (Fig. 2, part e).

STONE-BANKED TERRACES

Stone-banked terraces, where the risers are free of vegetation, are rare on Macquarie Island and have not, to our knowledge, previously been described. One group occurs 500 m west of Spot Height 318, at about 300 m a.s.l. (Fig. 1). The terraces are small steps on a 15° slope facing northwest. Average riser height is 0.07 m and average tread width 0.6 m. The surface gravels are mostly 0.015–0.025 m in size but smaller gravels down to 0.005 m are present. The risers often have one or two large stones to 0.07 m on them, presumably contributing to the banking of the riser. There

are discrete small clumps of *Azorella macquariensis*, *Coprosma perpusilla*, and mosses *Racomitrium crispulum* and *Ditrichum strictum* scattered on the treads only.

A second group of stone-banked terraces occurs in a small, sparsely vegetated area on the plateau 750 m west of Mount Elder (Fig. 1) at about 300 m a.s.l. They take the form of lobes with risers about 0.3 m high, banked by clasts up to 0.02–0.03 m in diameter. They occur on a saturated and extremely exposed west-facing slope of about 5° where solifluction and freeze-thaw processes are active.

Discussion

INFLUENCES ON TERRACE MORPHOLOGY ON MACQUARIE ISLAND

The variety of terrace forms present on Macquarie Island results from the interaction between environmental factors (including wind, frost regimes, slope, aspect, and water) with the bare graveled areas and vegetation.

Wind

At the Macquarie Island meteorological station at 6 m a.s.l. the winds are overwhelmingly from the west and northwest, with

an annual average wind speed of 9.7 m s^{-1} (Bureau of Meteorology, 2012). Detailed meteorological data is not available for other locations on Macquarie Island. Selkirk and Saffigna (1999) found no difference in predominant wind direction between their study site at 180 m a.s.l. on the western margin of the plateau and the meteorological station site, although De Lisle (1965) and Peterson and Scott (1988) have suggested that the meteorological station would be sheltered from southwesterly to southerly winds. Short-term measurements and estimations of wind speeds on the plateau have been made periodically. Taylor (1955) estimated plateau wind speeds to be a minimum of 25% higher, Jenkin (1975) 32% higher, and Löffler (1983) up to 100% higher than at the meteorological station.

The data from this study show variations in wind velocity across the two main terrace types. The mean velocity measured over the east-facing sites was 2.7 ± 0.1 m s^{-1}, and over the west-facing sites was 3.5 ± 0.1 m s^{-1}. Despite the small differences in some instances, the variation may be enough to play a role in maintaining the terrace landform at all sites. Vegetation expansion and deposition of mineral material occur in the calmer areas, and vegetation damage and erosion of mineral material occur in the more exposed positions of both types of terraces recognized by Taylor (1955).

Ashton and Gill (1965), considering wind damage to vegetation on windward slopes on Macquarie Island, suggested that erosion may be less severe at the edges (sides) of cushions due to eddy effects, allowing lateral expansion and ultimately an elongated stripe at right angles to wind direction. Around cushions of *Azorella selago* at Tafelberg on Marion Island, Haussmann et al. (2009a) found no difference in extent of erosion adjacent to cushions between sides, windward, or downwind locations.

Frost

On the plateau above 200 m a.s.l. the likely annual number of frost days can be calculated using Bureau of Meteorology temperature data collected at 6 m a.s.l., allowing for the lapse rate. However, the calculated lapse rate varies from 0.3 to 1.0 °C per 100 m rise in altitude (Taylor, 1955; Jenkin, 1975; Löffler, 1983; Tweedie and Bergstrom, 2000), so the calculated number of frost days also varies. In producing patterned ground, the number of freeze-thaw cycles rather than the total number of days with frost is important. The number of freeze-thaw cycles experienced above 200 m will be fewer than the number of frost days, as in some locations, mainly during winter, thawing will not occur. Löffler (1983) estimated 170 frost-change days (i.e. freeze-thaw cycles) at 200 m a.s.l., while Tweedie (personal communication, 2000) measured 196 above- and below-ground freeze-thaw cycles at 200 m a.s.l. on Mount Elder in the period September 1996 to October 1997. On Marion Island, at 300 m a.s.l. at Tafelberg, Haussmann et al. (2009b) recorded more than 200 frost cycles adjacent to *Azorella selago* cushions from April to November in 2007.

Löffler et al.(1983), Peterson et al. (1983), and Selkirk (1998) have all described frost sorting of surface gravels on terraces. On west-facing slopes, frost-sorted stripes oriented at right angles to the terraces and contours are common on the bare areas. Sorting of the gravels on west-facing terraces thus contrasts with that on terraces on east-facing slopes, where sorting occurs parallel to the

terraces, with larger stones sorted to the outer edge of the treads, or as sorted polygons. Mark et al. (2001) described comparable active terraces in the Martial Valley in Tierra del Fuego where frost sorting moves larger stones on bare areas and sometimes onto the vegetated riser. At Tafelberg on Marion Island, Haussmann et al. (2009b) found differences in particle size around cushions, with coarser material accumulating on the upslope side.

Frost sorting and solifluction are important in the present maintenance of the terrace form, though their role in development of the original form is unknown. Löffler (1983) regarded the ''leeward terraces'' as relict forms from an earlier period of periglacial conditions, but Selkirk (1998) showed the terraces to be presently active. Frost-controlled geomorphic processes certainly occur today on Macquarie Island as can be seen by the development of sorted polygons and stripes on the bare areas of the terraces and the discovery of stone-banked terrace forms. Such processes are important in the churning of bare areas, promoting erosion and inhibiting plant colonization (Bergstrom and Selkirk, 1999), thus maintaining the terrace forms.

In the Martial Valley in Tierra del Fuego, Brancaleoni et al. (2003) also described patterning of ground along contour lines. They found that, while established cushion plants provide suitable conditions for colonization, between vegetated areas frost heave, solifluction, and/or wind action are likely to damage plant seedlings. From their studies on Tafelberg, Marion Island, Haussmann et al. (2009a) suggested frost pull as the mechanism by which needle ice damages the roots of vulnerable plants such as seedlings with a single tap root.

Aspect

Environmental attributes such as insolation and exposure to wind also vary with aspect and may influence terrace form. Although suggested from elsewhere, for example Jan Mayen Island (Warren Wilson, 1952), insolation alone is unlikely to be adequate to explain terrace formation in the cloudy conditions of Macquarie Island.

The presence of terraces of different form on west-facing and east-facing slopes points to wind rather than insolation as the main factor linked to aspect. The aspect of the hillslope determines the position and velocity with which wind impacts on the vegetated or bare ground components of the terrace form.

Slope

Slope contributes to terrace form. The steeper the slope, the faster mineral material moves downslope under the influence of gravity and the harder it is for vegetation to become established and thus develop across the slope to form terraces parallel to the contour. West-facing slopes that are steeper than 15° do not support terraces but have widely spaced oval-shaped patches of vegetation scattered on them. On east-facing slopes, where terraces occur on slopes of up to 35°, tread and riser width vary considerably (Table 1) but dimensions generally decrease as slope steepens up a given hillside (e.g. Table 1: Site 1). This is comparable with observations of turf-banked solifluction terraces in Glacier National Park, Montana (Walsh et al., 2003; Butler et al., 2004). Increasing slope angle is one factor that tilts the long axis of the terraces away from the

J. M. Selkirk-Bell and P. M. Selkirk / 269
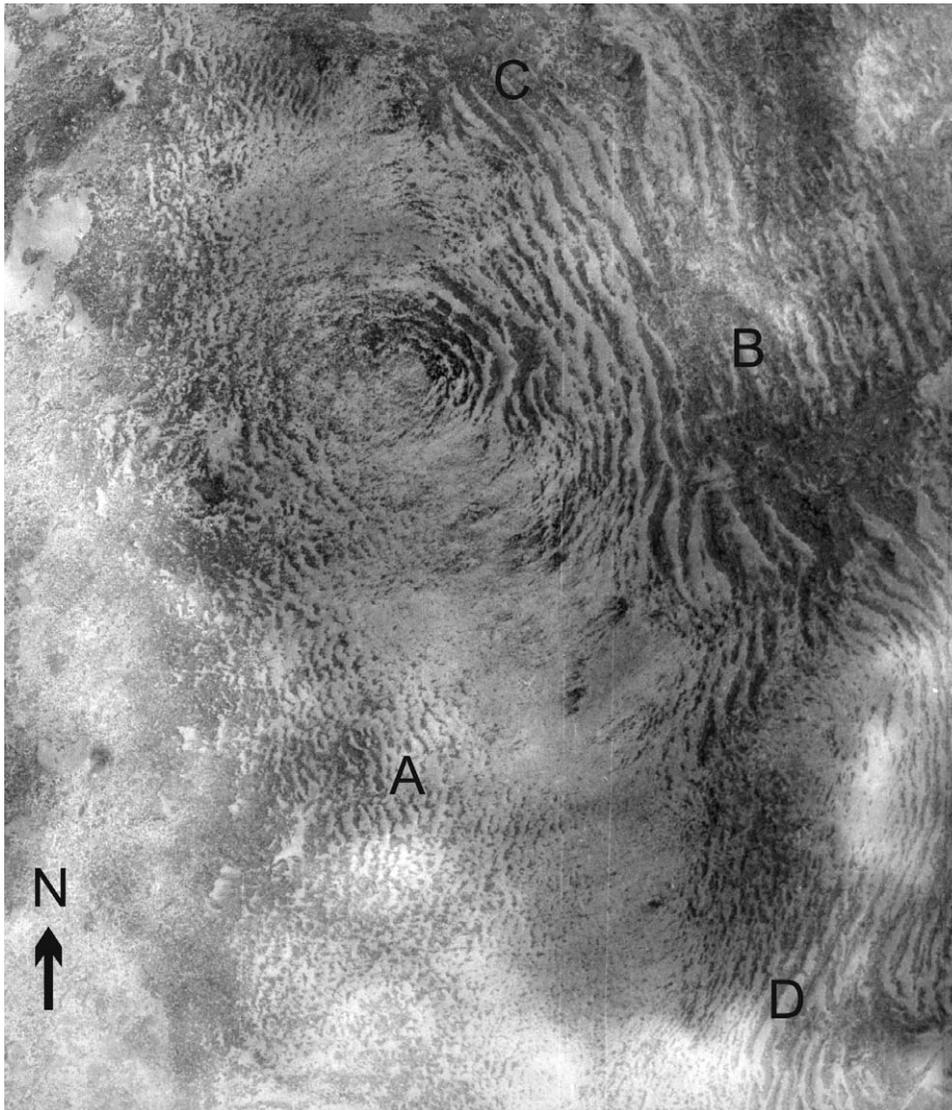
FIGURE 4. (a) Aerial photograph of a dome-shaped hill (location shown on Fig. 1) showing terrace morphologies. A shows contour parallel terraces on west-facing slopes; B indicates contour parallel terraces on east-facing slopes; C and D indicate terraces tilting down-to-west on north-facing and south-facing slopes, respectively. Due to lack of information available on flying height during aerial photography, scale approximate only, 1:1000. 1976 Commonwealth of Australia Series CAS 8467, Run 3, Frame 6. © Commonwealth of Australia (Geoscience Australia) 2013. This product is released under the Creative Commons Attribution 3.0 Australia Licence.

horizontal, eventually leading to a breakup of the linear form into irregular patches (e.g. Table 1: Sites 33, 39). Selkirk et al. (1988) drew attention to a relationship between hillslope angle and tilt of terraces, but did not discuss the processes involved or the possible involvement of factors other than slope.

Mark et al. (2001) described 6°–15° lateral tilt along turf-banked terraces at their study site in Tierra del Fuego. They described the lateral tilt as ''curious,'' had no explanation for its origin, but—although the role of wind in terrace formation there has not been determined—they felt it was unlikely to have a major role in accounting for the lateral slope of the terraces.

Water

Wind-borne hail, ice, and rain, as well as falling liquid rain, mist, and melting snow impact on terrace morphology. Overland and groundwater flow are important in maintaining the form of east-facing terraces (Selkirk, 1998) as the movement of water-lubricated gravels along the tread is too rapid for vegetation establishment.

Gallart et al. (1993) successfully simulated terrace morphology with a computer model that inputs parameters of vegetation (such as establishment, age, living points, and growth) and geomorphic processes associated with slopewash. However, the simulation did not attempt to model geomorphic processes other than slopewash and does not produce terrace forms that tilt downslope away from contour parallel.

The snow accumulation pattern depends upon the steepness of the slope and the aspect of the terraces with relation to wind. On steeper east-facing slopes snow accumulation covers the vegetated riser and most of the graveled tread, leaving only the top of the riser and the front of the tread exposed. On gentler slopes, snow accumulation is restricted to the riser and the rear of the tread. When snowmelt occurs, our observations show that the water is channeled along the slope of the graveled treads and chutes in the already-established terrace forms.

On terraces on west-facing slopes, most snow accumulates at the cliffed vegetation face (Fig. 2, part d). This snow appears to
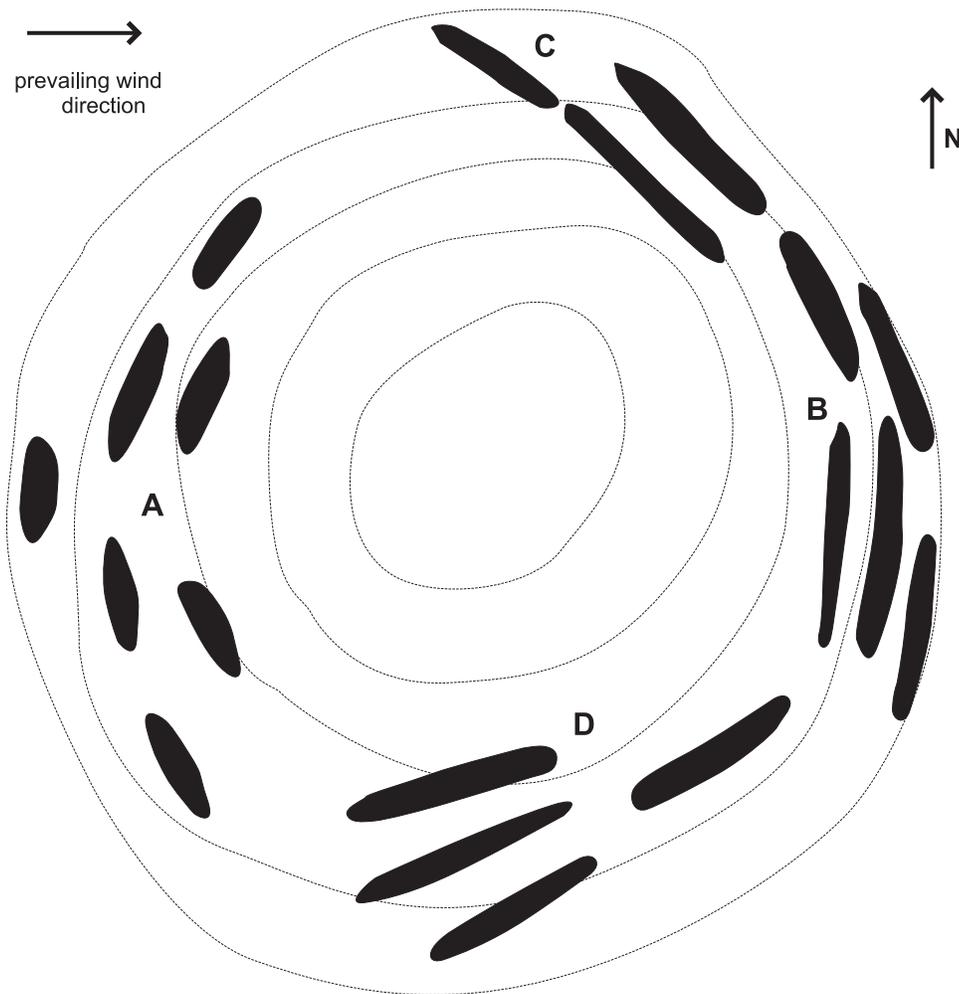
A   contour parallel terraces on west-facing slope

B   contour parallel terraces on east-facing slope

C   east-facing style terraces dipping to west on north-facing slope

D   east-facing style terraces dipping to west on south-facing slope

FIGURE 4. (b) Idealized hill showing terrace morphology relative to aspect and wind direction.

be packed more firmly into the vegetation than on the east-facing sites, presumably due to packing by wind. There is also minor snow accumulation at the upslope edge of the vegetation. Snowmelt at these sites runs downslope on the gravel, either staying in the graveled areas flowing onto the rear of the vegetated treads, or flowing around the ends of the vegetated strips. Butler and Malanson (1989) pointed to the importance of snowmelt in facilitating sediment movement on terraces. We have observed snowmelt entraining small particles and depositing them on the upslope vegetation edges in the west-facing forms.

Vegetation

The dominant plant species in terraced areas are bryophytes and the vascular cushion plant *Azorella macquariensis,* but many other species occur (Tables 1 and 2). Taylor (1955) attributed the establishment of terraces on east-facing slopes to accumulation of mineral material behind *A. macquariensis* cushions under the influence of the strong westerly winds. The risers of these terraces can also be vegetated by other short herb vegetation; *A. macquariensis* is not a necessary component of the vegetation forming the risers. The vegetation-gravel contact on the terraces varies and can

be cliffed, undercut, or have a vegetation skirt growing onto the tread (Selkirk et al., 1988).

Morphology of the spectacular terraces on the Macquarie Island plateau reflects interactions on sloping surfaces between suitable vegetation, mobile gravel with suitable size characteristics, wind, and several states of water under appropriate climatic conditions. Changes to any one of these components may well result in changes to this landscape. In the vegetation-banked terraces, *A. macquariensis* is the predominant vegetation component, with significant component of the mosses *Racomitrium crispulum* and *Ditrichum strictum* amongst *A. macquariensis* in risers and on treads. Where both risers and treads are vegetated, the gravel surface becomes fully stable. Depletion of *A. macquariensis* and moss species in the terrace vegetation may result in destabilization of the gravel surface, allowing more extensive gravel movement under the influence of wind and water (rain, hail, overland flow, snowmelt, and frost), and potentially significant geomorphic changes on the plateau of Macquarie Island. Alternately, as terraces can be vegetated by plants other than *A. macquariensis* and moss, e.g. *Agrostis magellanica* and *Luzula crinita*, with changes to the environment the terracing may persist but with different species forming the vegetation bands.

Since 2009 there have been dramatic changes observed in the plateau vegetation on Macquarie Island. *Azorella macquariensis* cushions and swards of mosses have browned and grayed, followed by wind erosion of the dead plants, leaving bare ground in their place. Although this phenomenon is under active study it is not yet clear whether the changes in plant health result from the impact of one or more pathogens, climate change, or a combination of factors (Department of Primary Industries, Parks, Water and Environment, 2012).

Our observations of 1979–1980 to 1994–1995, of which samples are recorded in Tables 1, 2, and 3, and which form the basis of our interpretation of the processes involved in the maintenance of the terraces, predate the changes at present occurring which are under study by others. The observations provide a valuable record of the situation preceding the changes since 2009 and will be useful in evaluating the environmental changes that have already begun.

A NEW MODEL OF TERRACE MORPHOLOGY ON MACQUARIE ISLAND

We believe that the relation between terrace forms on east-facing and west-facing slopes [Taylor's (1955) leeward and windward terraces] can be understood by focusing on two contrasting areas within each type of terrace: where plant growth and soil accretion occur; and where plant damage and soil erosion occur.

Cross sections of terraces on Macquarie Island reveal the interrelationships of various terrace morphologies. As can be seen on Figure 5, erosion and vegetation damage (E″) occur in all cases at the wind-exposed edge of the vegetation, and accretion and vegetation growth (A″) occur in all cases at the protected edge of the vegetation. Figure 2, parts e and f, shows examples of these. On west-facing slopes (Fig. 2, part f), E″ is located at the downslope side (the cliffed edge) of the vegetation patch, and on the east-facing slopes (Fig. 2, part e) it is at the upslope edge of the vegetation patch (the crest of the riser). Accretion and vegetation growth (A″) take place on the least-exposed side of the vegetation patch. On west-

facing slopes, this is the upslope side and on east-facing slopes this is the downslope side. In the case of near-horizontal surfaces shown in Figure 5, the pattern is also repeated, though erosion of surrounding mineral material may produce raised vegetation patches.

Terraces on north- and south-facing slopes tilt down towards the west rather than towards the east, however they have the same pattern of erosion/accretion and vegetation damage/growth as terraces on east-facing slopes. The tilt downward to the west minimizes the impact of the prevailing westerly wind on the vegetation of the steep risers, which are more sheltered than the gravel treads. Terrace patterning means that the surfaces on which the prevailing wind impacts most severely are the bare gravel treads. Erosion and vegetation damage still occur at the outer edge of the gravel where wind velocity is great, and vegetation growth and accretion occur on the comparatively wind-sheltered riser downslope.

Conclusions

Vegetated terraces occurring in different positions on the upland plateau of Macquarie Island vary in morphology: in the shape, size, and proportion of vegetated and graveled surfaces, and the species of plants present. Although previous work identified two separate and unrelated terrace types, we have shown that they are two related forms that grade into one another: the processes acting on vegetated and mineral surfaces are the same, but different terrace morphologies depend on hillside aspect in relation to incident wind. The terrace form that develops is the result of the complex interaction of slope, aspect, gravel, and vegetation with the prevailing climatic conditions.

Climate change is clearly underway in the subantarctic, at least in the short to medium term, with records showing increasing temperatures, increasing wind speed, and changes in precipitation, and with models showing these trends are likely to continue through the present century (Pendlebury and Barnes-Keoghan, 2007; Adams, 2009). On Macquarie Island total precipitation has increased with an increase in the number of cyclonic events crossing the island, but the atmosphere is windier and drier, leading to drying of the island's surface (Adams, 2009). Change is also occurring to the plateau vegetation on Macquarie Island, with the widespread death of cushion plants and moss (Department of Primary Industries, Parks, Water and Environment, 2012). Future studies will show how the spectacular terraced landscape of the Macquarie Island plateau responds to changes in the environmental components that influence terrace morphology.

Acknowledgments

FIGURE 5. Cross sections of terraced hillsides showing terrace morphologies and interrelationships.

Legend within figure:
- West / East
- hypothetical slopes
- A: moderate to steep west - facing slopes (>15°)
- B: gentle west - facing slopes (5 - 15°)
- near horizontal slopes
- C: gentle to moderate east - facing slopes (5-25°)
- D: steep east - facing slopes (>25°)

- fully vegetated or nearly so
- mineral material bare of vegetation or nearly so
- E" erosion of mineral material and damage to vegetation
- A" accretion of mineral material and potential growth of vegetation
- prevailing wind direction
- 1 m

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References Cited

Adams, N., 2009: Climate trends at Macquarie Island and expectations of future climate change in the sub-Antarctic. *Papers and Proceedings of the Royal Society of Tasmania*, 143(1): 1–8.

Ashton, D. H., and Gill, A. M., 1965: Pattern and process in a Macquarie Island feldmark. *Proceedings of the Royal Society of Tasmania*, 79: 235–245.

Bergstrom, D. M., and Selkirk, P. M., 1999: Bryophyte propagule banks in feldmarks on subantarctic Macquarie Island. *Arctic, Antarctic, and Alpine Research*, 31: 202–208.

Brancaleoni, L., Strelin, J., and Gerdol, R., 2003: Relationships between geomorphology and vegetation patterns in subantarctic Andean tundra of Tierra del Fuego. *Polar Biology*, 26: 404–410.

Bureau of Meteorology, 2012: Australian Government, Climate statistics for Australian locations, Monthly climate statistics Macquarie

Island. <//www.bom.gov.au/climate/averages/tables/cw_300004_All.shtml>, accessed 25 June 2012.

Butler, D. R., and Malanson, G. P., 1989: Periglacial patterned ground, Waterton-Glacier International Peace Park, Canada and U.S.A. *Zeitschrift für Geomorphologie*, N.F. 33: 43–57.

Butler, D. R., Malanson, G. P., and Resler, L. M., 2004: Turf-terrace treads and risers, turf exfoliation and possible relationships with advancing treeline. *Catena*, 58: 259–274.

De Lisle, J. F., 1965: The climate of the Auckland Islands, Campbell Island, and Macquarie Island. *New Zealand Ecological Society Proceedings*, 12: 37–44.

Department of Primary Industries, Parks, Water and Environment, 2012: Tasmanian Threatened Species Listing Statement. *Azorella macquariensis* (Macquarie cushions). <//www.dpiw.tas.gov.au/inter.nsf/Attachments/LJEM-82NVTX/$FILE/Azorella%20macquariensis%20listing%20statement.pdf>, accessed 9 February 2012.

Douglas, T. G., and Harrison, S., 1996: Turf-banked terraces in Öraefi, southeast Iceland: morphometry, rates of movement, and environment controls. *Arctic and Alpine Research*, 28: 228–236.

Eddy, J., Humphreys, G. S., Hart, D. M., Mitchell, P. B., and Fanning, P. C., 1999: Vegetation arcs and litter dams: similarities and differences. *Catena*, 37: 57–73.

Gallart, F., Puigdefábregas, J., and del Barrio, G., 1993: Computer simulation of high mountain terracettes as interaction between vegetation growth and sediment movement. *Catena*, 20: 529–542.

George, A. S., Orchard, A. E., Hewson, H., and Thompson, H. S. (eds.), 1993: *Flora of Australia*. Vol. 50, Oceanic Islands 2. Canberra: Australian Government Publishing Service, 606 pp.

Hall, K., 1983: Observations of some periglacial features and their palaeoenvironmental implications on sub-Antarctic islands Marion and Kerguelen. *South African Journal of Antarctic Research*, 13: 35–40.

Hansen-Bristow, K. J., and Price, L. W., 1985: Turf-banked terraces in the Olympic Mountains, Washington, U.S.A. *Arctic and Alpine Research*, 17: 261–270.

Harris, C., 1982: The distribution and altitudinal zonation of periglacial landforms, Okstindan, Norway. *Zeitschrift für Geomorphologie*, 26(3): 283–304.

Haussmann, N. S., Boelhouwers, J. C., and McGeoch, M. A., 2009a: Fine scale variability in soil frost dynamics surrounding cushions of the dominant vascular plant species (*Azorella selago*) on sub-Antarctic Marion Island. *Geografisker Annaler*, 91A(4): 257–268.

Haussmann, N. S., McGeoch, M. A., and Boelhouwers, J. C., 2009b: Interactions between a cushion plant (*Azorella selago*) and surface sediment transport on sub-Antarctic Marion Island. *Geomorphology*, 107: 139–148.

Inoue, H., and Seppelt, R. D., 1985: Notes on the genus *Plagiochila* (Dum.) Dum. from subantarctic Macquarie Island. *Bulletin of the National Science Museum Tokyo, Series B (Botany)*, 11(4): 119–126.

Jahn, A., 1958: Periglacial microrelief in the Tatras and on the Babia Gora. *Biuletyn Peryglacjalny*, 6: 227–249.

Jenkin, J. F., 1975: Macquarie Island, subantarctic. *In* Rosswall, T., and Heal, O. W. (eds.), *Structure and Function of Tundra Ecosystems*. Stockholm: *Ecological Bulletin*, 20: 375–397.

Kantvilas, G., and Seppelt, R. D., 1992: The lichen flora of Macquarie Island: introduction and an annotated checklist of species. *ANARE Research Notes*, 87: 1–20.

Löffler, E., 1983: Macquarie Island—eine vom Wind geprägte Naturlandschaft in der Sub-Antarktis. *Polarforschung*, 53(1): 50–74.

Löffler, E., Sullivan, M. E., and Gillison, A. N., 1983: Periglacial landforms on Macquarie Island, subantarctic. *Zeitschrift für Geomorphologie*, N.F. 27(2): 223–236.

Lynch, A. J. J., and Kirkpatrick, J. B., 1995. Pattern and process in alpine vegetation and landforms at Hill One, Southern Range, Tasmania. *Australian Journal of Botany*, 43: 537–554.

Mark, A. F., Dickinson, K. J. M., Allen, J., Smith, R., and West, C. J., 2001: Vegetation patterns, plant distribution and life form across the alpine zone in southern Tierra del Fuego, Argentina. *Austral Ecology*, 26: 423–440.

McCarthy, P. M., 2003: *Catalogue of Australian Liverworts and Hornworts.* Canberra: Australian Biological Resources Study, 137 pp.

Ochyra, R., and Broughton, D. A., 2004: New moss records from the Falkland Islands. *Journal of Bryology*, 26(3): 226–230.

Pendlebury, S. F., and Barnes-Keoghan, I. P., 2007: Climate and climate change in the sub-Antarctic. *Papers and Proceedings of the Royal Society of Tasmania*, 141(1): 67–81.

Peterson, J. A., and Scott, J. J., 1988: Interrelationships between wind exposure, vegetation distribution and pollen fallout between Bauer Bay and Sandy Bay, Macquarie Island. *Papers and Proceedings of the Royal Society of Tasmania*, 122(1): 247–254.

Peterson, J. A., Scott, J. J., and Derbyshire, E., 1983: Australian landform example no. 43, sorted stripes of periglacial origin. *Australian Geographer*, 15(5): 325–328.

Rózycki, S., 1986: Structures pseudopériglaciaires au Sahara Central. *Biuletyn Peryglacjalny*, 30: 125–126.

Selby, M. J., 1971: Some solifluction surfaces and terraces in the ice-free valleys of Victoria Land, Antarctica. *New Zealand Journal of Geology and Geophysics*, 14(3): 469–476.

Selkirk, J. M., 1998: Active vegetation-banked terraces on Macquarie Island. *Zeitschrift für Geomorphologie*, N.F. 42(4): 483–496.

Selkirk, J. M., and Saffigna, L. J., 1999: Wind and water erosion of a peat and sand area on subantarctic Macquarie Island. *Arctic, Antarctic, and Alpine Research*, 31(4): 412–420.

Selkirk, P. M., and Adamson, D. A., 1998: Map of structural vegetation types and drainage on subantarctic Macquarie Island. Details about the compilation and interpretation of the map. <//data.aad.gov.au/metadata/other_data/macca_veg_map_doco.html>, accessed 3 March 2013.

Selkirk, P. M., Adamson, D. A., and Seppelt, R. D., 1988: Terrace form and vegetation dynamics on Macquarie Island. *Papers and Proceedings of the Royal Society of Tasmania*, 122(1): 83–90.

Seppelt, R. D., 2004: *The Moss Flora of Macquarie Island.* Kingston, Australia: Australian Antarctic Division, 328 pp.

Taylor, B. W., 1955: Terrace formation on Macquarie Island. *Journal of Ecology*, 43: 133–137.

Tweedie, C. E., and Bergstrom, D. M., 2000: A climate change scenario for surface air temperature at subantarctic Macquarie Island. *In* Davison, W., Howard-Williams, C., and Broady, P. (eds.), *Antarctic Ecosystems: Models for Wider Understanding.* Christchurch: New Zealand Natural Sciences, 272–281.

Walsh, S. J., Bian, L., McKnight, S., Brown, D. G., and Hammer, E. S., 2003: Solifluction steps and risers, Lee Ridge, Glacier National Park, Montana, USA: a scale and pattern analysis. *Geomorphology*, 55: 381–398.

Warren Wilson, J., 1952: Vegetation patterns associated with soil movement on Jan Mayen Island. *Journal of Ecology*, 40(2): 249–264.