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A method for assessing the physical recovery of Antarctic desert pavements following human-induced disturbances: A case study in the Ross Sea region of Antarctica

Tanya A. O'Neill [a,b,*], Megan R. Balks [b], Jerónimo López-Martínez [c], Judi L. McWhirter [d]

[a] *Landcare Research, Manaaki Whenua, Private Bag 3127, Hamilton, New Zealand*
[b] *Department of Earth and Ocean Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand*
[c] *Geología y Geoquímica, Facultad de Ciencias, Universidad Autónoma de Madrid, 28049 Madrid, Spain*
[d] *Department of Statistics, University of Waikato, Private Bag 3105, Hamilton, New Zealand*

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ABSTRACT

With increasing visitor numbers an understanding of the impacts of human activities in Antarctic terrestrial environments has become important. The objective of this study was to develop a means for assessing recovery of the ground surface desert pavement following physical disturbance. A set of 11 criteria were identified to assess desert pavement recovery. Assessed criteria were: embeddedness of surface clasts; impressions of removed clasts; degree of clast surface weathering; % overturned clasts; salt on underside of clasts; development of salt coatings; armouring per m^2; colour contrast; evidence of subsidence/melt out; accumulation of salt on cut surfaces; and evidence of patterned ground development. Recovery criteria were assigned a severity/extent rating on a scale from zero to four, zero being highly disturbed, and four being undisturbed. A relative % recovery for each criteria was calculated for each site by comparison with a nearby undisturbed control area, and an overall *Mean Recovery Index* (MRI) was assigned to each pavement surface.

To test the method, 54 sites in the Ross Sea region of Antarctica were investigated including areas disturbed by: bulldozer scraping for road-fill, contouring for infrastructure, geotechnical investigations, and experimental treading trial sites. Disturbances had occurred at timescales ranging from one week to 50 years prior to assessment. The extent of desert pavement recovery at the sites investigated in this study was higher than anticipated. Fifty of the 54 sites investigated were in an intermediate, or higher, stage of desert pavement recovery, 30 sites were in an advanced stage of recovery, and four sites were indistinguishable from adjacent control sites (MRI = 100%). It was found that active surfaces, such as the gravel beach deposits at the Greenpeace World Park Base site at Cape Evans, the aeolian sand deposits at Bull Pass, and the alluvial fan deposits of the Loop Moraine field campsite, recovered relatively quickly, whereas less active sites, such as the bulldozed tracks at Marble Point, and Williams Field to McMurdo Station pipeline site on Ross Island, showed only intermediate recovery 20–30 years after disturbance. The slabby grano-diorite surface material at the former Vanda Station site, meant that the impacts that had occurred were hard to detect following decommissioning of the station and site remediation. Desert pavements disturbed by randomly dispersed footprints, temporary field campsites at the Loop Moraine and VXE6 Pond in the Wright Valley, recovered to be undetectable (MRI = 100%) within five years, whereas track formation from repeated trampling, particularly the concentration of larger clasts along the margin of a confined track, persisted for over 15 years (MRI = 82%). The recovery assessment method developed in this study has environmental management applications and potential to advance our ability to predict the recovery of desert pavement following human impacts from activities in Antarctica.

1. Introduction

Soils and land surfaces of most of the ice-free areas in the Ross Sea region of Antarctica have evolved as a result of slow weathering over long time periods, in an environment governed by low precipitation, severe cold (mean annual air temperatures <−10 °C),

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* Corresponding author. Landcare Research, Manaaki Whenua, Private Bag 3127, Gate 10, Silverdale Road, Hamilton 3240, New Zealand. Tel.: +64 7859 3744.
E-mail address: oneilltanya@hotmail.com (T.A. O'Neill).

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limited biological activity, and extraordinary landscape stability (Campbell and Claridge, 1987). Antarctic soils generally lack structural development and coherence, and as a consequence, most ice-free areas are readily disturbed by human activities, and slow to recover (Balks et al., 1995; Campbell and Claridge, 1987; Campbell et al., 1993; Claridge et al., 1995; Sheppard et al., 1994). There were more than 60 scientific stations and over 36,000 visitors to the Antarctic in the 2009/2010 summer season (IAATO, 2011). Human influence and impacts are greatest in the vicinity of the bases, such as at Hut Point Peninsula on Ross Island, where the United States and New Zealand Antarctic programmes are estimated to have catered for close to 100,000 people since the late 1950s (Tin et al., 2009). The McMurdo Dry Valleys, and Antarctic mainland coastal margins in the Ross Sea region are estimated to have been visited by about 15,000 people since the 1950s (Tin et al., 2009). With increasing visitor numbers, understanding the effects of human impacts on soil resources has become an important issue in Antarctica (Campbell et al., 1994; Chwedorzewska and Korczak, 2010).

Desert pavements play an important role in the Antarctic cold desert environment, acting as protective armour to stabilize both the slope and the soil. Mature, undisturbed Antarctic desert pavements are typically characterised by a closely packed layer of gravel, cobble, and boulder sized rock material, which can be ventifacted, and coated with desert varnish. Clasts are embedded into a finer matrix; and their undersides are often coated in salts. The clasts are not usually strongly cemented to one another or the substrate beneath. Consequently, once the protective armour of the desert pavement is lost, the underlying fine grained fraction becomes vulnerable to wind and water erosion. Freeze–thaw processes, wind action, and to lesser extent, water action, are recognised as drivers of physical weathering and desert pavement recovery, in polar desert environments (Bockheim, 2010; Campbell and Claridge, 1987; Campbell et al., 1998a). Wind is likely to be the primary driver of desert pavement recovery in most environments in the Ross Sea region (Campbell et al., 1998a).

Desert pavement disturbance can arise from a number of sources ranging from vehicles, that cause overturning of large cobbles, indentation and compression of sub-pavement soils; bulldozer blade scrapes; telecommunications antenna and pipeline installation; active layer removal for road or fill material; and scientific investigations; through to lower level disturbance from camping and pedestrian traffic. There have been limited previous studies on the ability of the Antarctic desert pavement to recover from human disturbances. Salt accumulation on recently disturbed surfaces (Balks et al., 1995; Campbell and Claridge, 1987) has been reported and it has been recognised that older weathering stage 4, 5, and 6 desert pavements are more vulnerable to disturbance (Campbell and Claridge, 1987). Campbell et al. (1993) developed a visual site assessment (VSA) for rapid evaluation of present day disturbance impacts. The VSA rates the extent of surface disturbance against impact assessment criteria, such as evidence of boot imprints, and evidence of foreign objects, as a means of comparing disturbance severity across different sites. The effects of earth moving activities on patterned ground were investigated on 1959-era cut and fill surfaces at Marble Point (Campbell et al., 1994), where slumping, surface salt efflorescences, and changes to the distribution of patterned ground was observed. The rate of walking track formation was investigated near Scott Base and in the McMurdo Dry Valleys, and showed that on some unconsolidated parent materials it takes less than 20 passes for a track to form (Campbell et al., 1998a). A study by Roura (2004) reported the relatively quick recovery of the former Greenpeace World Park Base site at Cape Evans, and showed the advantages of utilising young and active surfaces comprising beach gravels. McLeod (2012) identified differences in soil vulnerability across a variety of landforms and parent materials in the Wright Valley of the McMurdo Dry Valleys.

The objective of this study was to formulate a simple field-based method to quantify the relative stage of desert pavement recovery following physical disturbance. Our aim was to then test the Desert Pavement Recovery Assessment method on a range of previously disturbed sites comprising a variety of parent materials, landforms, and initial disturbance intensities.

2. Desert Pavement Recovery Assessment method

Eleven morphological features were identified to assess desert pavement recovery following disturbance (Table 1). A rating system was defined for each of the recovery criteria (Table 2). Recovery criteria I–VI relate to surface clast characteristics; VII and VIII are desert pavement attributes; and IX–XI are indicators of surface stability. Recovery criteria were assigned a severity/extent rating on a scale from zero to four, zero being highly disturbed, and four being undisturbed (Table 2). Examples of the recovery criteria are shown in Figs. 1–3.

The Desert Pavement Recovery Assessment (DPRA) method categorises the stage of recovery for each criteria along a continuous spectrum of desert pavement rehabilitation. The development

Table 1
Morphological features identified for assessment of desert pavement recovery.

Desert Pavement Recovery Assessment criteria (I–XI)	
Surface clast characteristics	
I	*Embeddedness of surface clasts* refers to the proportion of the clast below the ground surface level. Disturbance can leave clasts "perched" on the surface, or up-ended or double-stacked; whereas mature pavement surfaces are characterised by a smooth layer of adjacently packed flat-lying clasts.
II	*Impressions of removed clasts* are the holes left when surface clasts are moved.
III	*Degree of clast surface weathering* assesses attributes such as roundness and faceting, ventifaction, pitting, and evidence of polish.
IV	*% overturned clasts* were estimated by the proportion of clasts that are overturned as a result of disturbance, with fresh overturns being clearly visible due to salt coatings (previously underneath) exposed on the upturned clast.
V	*Salt on underside of clasts* was determined using ten randomly selected cobbles and noting the proportion of clasts with salt visible on the underside.
VI	*Development of salt coatings* on the undersides of clasts was assessed based on the ten cobbles tested in V above, and the absence/presence, patchiness, and thickness, of the salt coating was assessed.
Desert pavement attributes	
VII	*Armouring (*1 m^2 *test plot).* Desert pavement takes on an armoured appearance over time as finer fragments are fretted from the surface, and fine underlying material winnowed away, to form a well-packed surface layer of interlocking material.
VIII	*Colour contrast (munsell unit difference).* Weathering processes are strongest at the surface and consequently the colour of the material below is paler than the surface material. A strong colour difference, defined by Campbell et al. (1993) as a colour contrast greater than three units apart (Munsell Soil Colour Chart), was evident on recently, and highly, disturbed surfaces, where the previously underlying material is obvious at the surface. A weak colour contrast occurred on surfaces where the natural weathering processes of recovery had begun.
Surface stability indicators	
IX	*Evidence of subsidence and melt-out* often results when active layer material has been removed, thereby causing melting of the newly exposed previous top of the permafrost beneath.
X	*Accumulations of salt on cut surfaces* commonly accompany physical disturbance where permafrost melting and evaporation has occurred.
XI	*Patterned ground development.* At recently disturbed sites the natural patterned ground may be lost due to surface re-contouring. Subsequent melting of the ice-wedges and winter freezing processes can help re-establish patterned ground.

Table 2
Desert Pavement Recovery criteria ratings.

Desert Pavement Recovery criteria		0 Highly disturbed	1 Clearly disturbed	2 Moderately disturbed	3 Weakly disturbed	4 Undisturbed
I	Embeddedness of surface clasts	None	Few	Some	Most	All
II	Impressions of removed clasts	Sharp/fresh	Clear	Distinct	Faint	Not visible
III	Degree of clast surface weathering (i.e. ventifaction, pitting, polish)	Unweathered	Weakly weathered	Moderately weathered	Strongly weathered	Very strongly weathered
IV	% overturned clasts	>75%	50–75%	20–50%	1–20%	0%
V	Salt on underside of clasts – "10 cobble" test	0–20%	20–40%	40–60%	60–80%	80–100%
VI	Degree of development of salt coatings	Not visible	Weakly developed	Moderately developed	Strongly developed	Very strongly developed
VII	Armouring (1 m^2 test plot)	0–20%	20–40%	40–60%	60–80%	80–100%
VIII	Colour contrast (munsell unit difference)	Very strong (>3)	Strong (3)	Moderate (2)	Weak (1)	Not visible (0)
IX	Evidence of subsidence and melt-out	Prominent	Distinct	Faint	Indistinct	Not visible
X	Accumulation of salt on cut surfaces	Abundant	Common	Some	Rare	Not visible
XI	Patterned ground development	Not visible	Indistinct	Faint	Distinct	Prominent

of desert pavement features is dependent on a range of factors including climate, parent material, and surface age. Therefore, to assess the recovery of a surface following disturbance it is necessary to make a comparison of the recovery criteria for the disturbed site with the recovery criteria assessed from an undisturbed site on the same soil-landscape unit.

To calculate a disturbed site's stage of desert pavement recovery, the relative % recovery for each criteria was calculated to establish the *Mean Recovery Index* (MRI):

$$\mathrm{MRI\%} = \left\{\left[\left(\mathrm{I^d}/\mathrm{I^c}\right) + \left(\mathrm{II^d}/\mathrm{II^c}\right) + \left(\mathrm{III^d}/\mathrm{III^c}\right) + \left(\mathrm{IV^d}/\mathrm{IV^c}\right) + \ldots\right]/11\right\}{*}100$$

where recovery criteria I through to XI and d = disturbed site, c = control site. The divisor, 11, reflects the number of recovery criteria. For example $\mathrm{IV^d}$ = the rating of criteria IV at the disturbed site.

If a criterion is not present in the control site, or the disturbed site, that criteria should be left out of the equation and the divisor must be adjusted to reflect the number of recovery criteria assessed.

The *Mean Recovery Index* (MRI) can be calculated for each site that is investigated. Overall stages of desert pavement recovery are defined (Table 3).

The DPRA method was tested at 54 disturbed, and adjacent control, sites and soil samples were collected. Site and soil descriptions were carried out in accordance with Schoeneberger et al. (2002).

3. Study sites

The Desert Pavement Recovery method was tested on 54 sites over the austral summers of 2008/09 and 2009/10 (Table 4). Sites included disturbed areas near: Scott Base, McMurdo Station, and Cape Evans, on Ross Island; the Wright and Taylor valleys in the McMurdo Dry Valleys; and Cape Roberts and Marble Point, on the Antarctic mainland coast (Fig. 4). Sites included areas disturbed by activities such as bulldozer scraping for road-fill, contoured for infrastructure, geotechnical investigation, and treading trial experimental sites; disturbed at timescales ranging from one week to 50 years prior to assessment (Fig. 5).

The sites on Ross Island were all formed from relatively unweathered scoriaceous basaltic material whereas sites on the Antarctic mainland were formed predominately from till materials of mixed lithology (Table 5). The Cape Evans and Cape Roberts sites were relatively active beach deposited material. The Ross Island, Marble Point, and Cape Roberts sites all have moderate snowfalls and are described as within the moist coastal mountain climatic zone of Campbell and Claridge (1987). The Wright Valley sites were all near the valley floor, in a central mountain climatic regime (Campbell and Claridge, 1987) where wind activity is the primary driver of surface processes.

Ross Sea region soils comprise a surface desert pavement and seasonally thawed active layer overlying permafrost. Soils of the study sites were formed from a range of parent materials (Table 5) but were uniformly coarsely textured (predominantly stony gravelly sands), and lacked cohesion and soil structural development. The gravimetric water content of the top 5 cm of soil ranged from 1 to 3% and soils were classed as subxerous to xerous (Campbell and Claridge, 1987). Soils were alkaline, with the pH in the range of 8–10 in the top 5 cm of soil, with small increases with depth. Electrical conductivity can show high spatial heterogeneity in Ross Sea region soils, and ranged between 0.04 mS/cm to 34.1 mS/cm in the top 5 cm of soil, decreasing with depth. Soils of the study sites had low nutrient contents, low organic carbon (0.02%–0.1%), very low total nitrogen (0–0.02%), and low C:N ratios (between 3 and 19). Details of soil analyses are included in O'Neill (2012).

4. Results of the application of the Desert Pavement Recovery Assessment method

The desert pavement recovery assessment of the disturbed study sites showed that 50 of the 54 sites investigated were in an intermediate, or higher, stage of desert pavement recovery and had MRIs greater than 50% (Tables 6 and 7). Thirty sites were in an advanced stage of recovery, with MRIs between 75% and 99%, and four sites had an MRI of 100% and were indistinguishable from adjacent control sites. Three sites showed a stage of incipient desert pavement formation, with MRIs between 25% and 49%, whilst one site had an MRI of 23% (recently or highly disturbed).

Sites showing the lowest MRI (Tables 6 and 7) and stage of desert pavement recovery were the Crater Hill site A, which was disturbed by vehicle traffic within the last 9 months at the Crater Hill Wind Farm (MRI = 23%) (Fig. 6); and the steep walking track in the Taylor Valley Visitor Zone (MRI = 39%) (Fig. 7).

At the other extreme, the four sites with MRIs of 100% (i.e. desert pavement recovery indistinguishable from adjacent control sites, Table 3) included the Crater Hill site C, disturbed 40–50 years prior; the Former Greenpeace World Park Base site, disturbed 18 years prior (Fig. 8a, b); the Taylor Valley Visitor Zone sand-rich till near the pro-glacial lake, disturbed less than one year prior; and the K123 Loop moraine field camp, tent site, disturbed 5 years prior to our investigation (Fig. 8c, d and e) (Tables 6 and 7).

Fig. 1. Examples of the Desert Pavement Recovery Assessment (DPRA) criteria I–V (Tables 1 and 2). a) Embeddedness of surface clasts, DPRA rating 1, clearly disturbed; b) embeddedness of surface clasts, DPRA rating 4, undisturbed; c) impressions of removed clasts, DPRA rating 0, highly disturbed (arrows indicate impression); d) degree of clast weathering, DPRA rating 2, moderately weathered (varnish and pitting); e) % overturned clasts (salt side up, circles indicate overturns), DPRA rating 2, moderately disturbed, 20–50% clasts overturned; f) salt on underside of clasts, as part of "10 cobble" test.

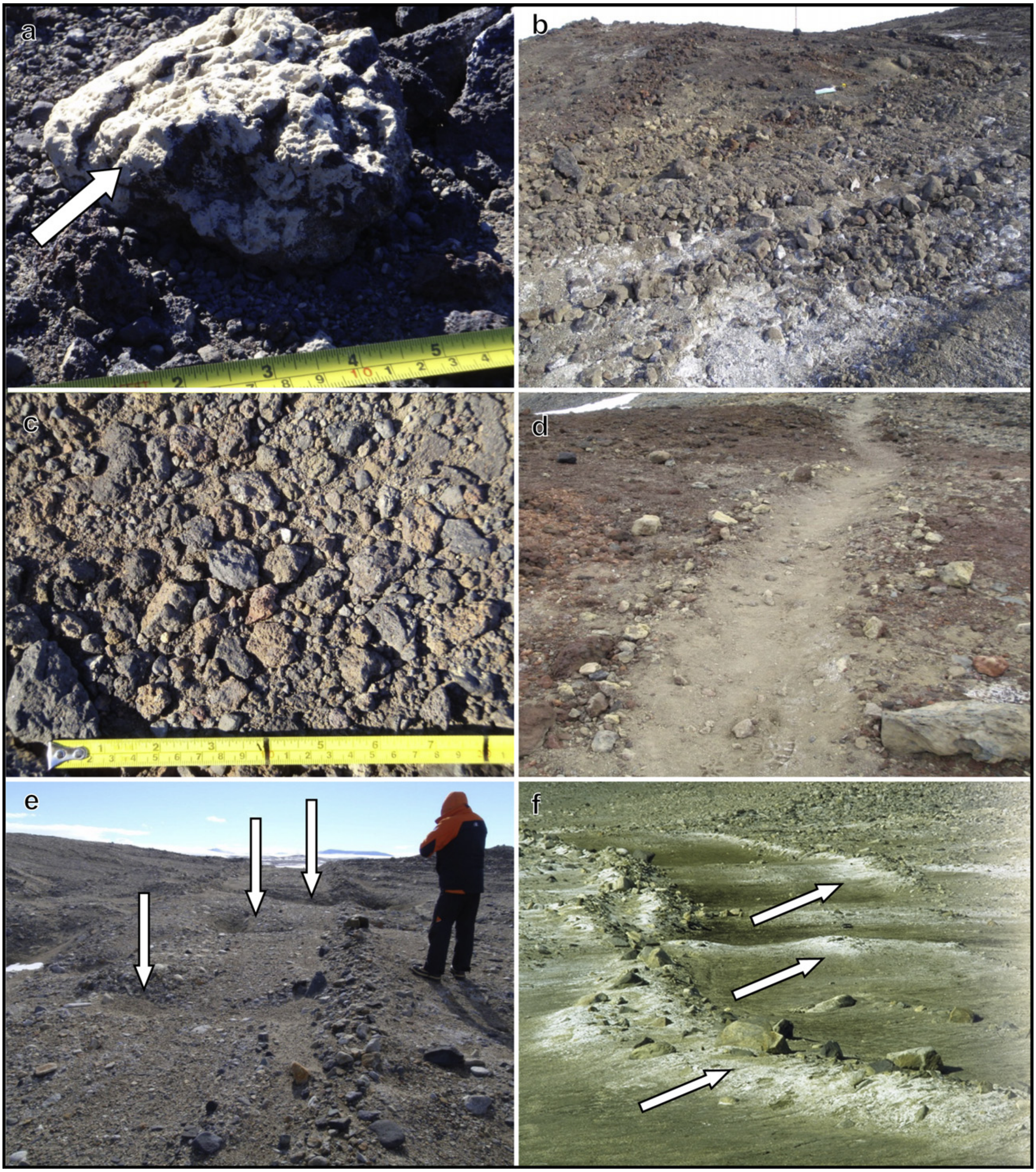

Fig. 2. Examples of the Desert Pavement Recovery Assessment criteria VI–X (Tables 1 and 2). a) Degree of development of salt coatings, DPRA rating 3, strongly developed; b) armouring (1 m^2 test plot), DPRA rating 0, highly disturbed; c) armouring (1 m^2 test plot), DPRA rating 3, weakly disturbed; d) colour contrast (munsell unit difference), DPRA rating 0, very strong (>3 units difference), highly disturbed; e) evidence of subsidence and melt-out (arrows indicate hollows), DPRA rating 0, prominent, highly disturbed; f) accumulation of salt on cut surfaces (arrows pointing to salt deposits), DPRA rating 0, abundant, highly disturbed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

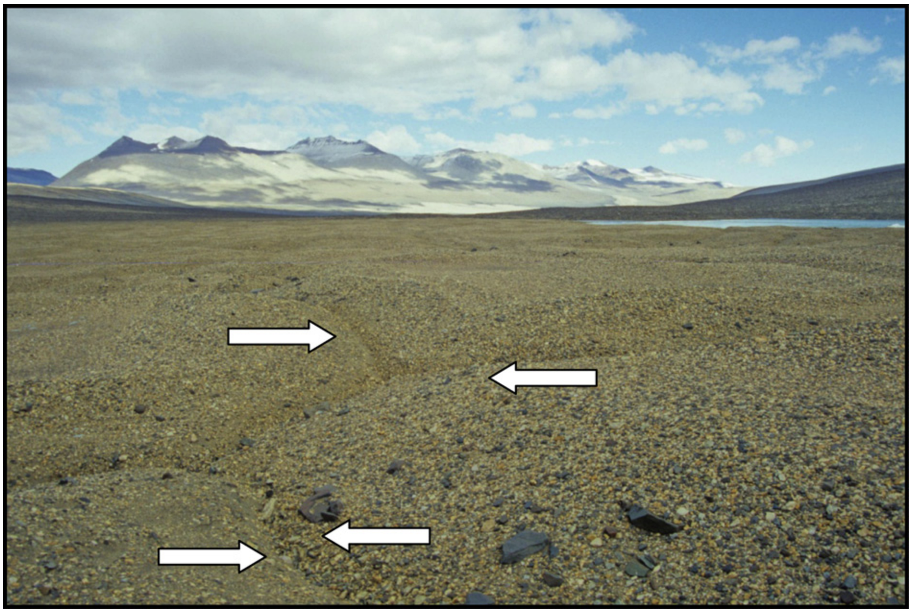

Fig. 3. Example of the Desert Pavement Recovery Assessment (DPRA) criteria XI (Tables 1 and 2). Patterned ground development, DPRA rating 4, prominent or undisturbed (arrows indicate patterned ground cracks).

Table 3
Stages of desert pavement recovery as a function of Mean Recovery Index (MRI).

MRI (%)	Recovery stage
0–24	Recently or highly disturbed
25–49	Incipient pavement
50–74	Intermediate recovery
75–99	Advanced recovery
100	Indistinguishable from control site

5. Discussion

5.1. Desert Pavement Recovery criteria

The 11 desert pavement recovery criteria used to quantify desert pavement recovery at 54 sites in the Ross Sea region of Antarctica provided a useful, semi-quantitative, method to assess desert pavement rehabilitation following physical disturbance. Overall, the extent of desert pavement recovery from the physical impacts of different scales of human activity was higher than anticipated.

The five recovery criteria to show greatest usefulness across the 54 study sites were: embeddedness of surface clasts (recovery criteria I); impressions of removed clasts (II); % overturned clasts (IV); armouring per m^2 (VII); and colour contrast (VIII).

Disturbance to the embeddedness of clasts within the desert pavement was particularly apparent when clasts which have pale-coloured salt coatings on their undersides are up-ended, double-stacked, or overlapping. Depending on the size of the clast, the impressions of removed and upturned clasts can persist for a long time in the Antarctic environment. In most Antarctic settings, wind is the primary driver for reorganisation of material and desert pavement rehabilitation, and processes such as infilling may take a long time (years to decades) to occur. For example, impressions of

Table 4
Location and disturbance history of the sites investigated.

Location	Site description	GPS location	Time since last disturbance	Cause of disturbance	Disturbed area (m^2)
Scott Base	Microbial Experiment site	77° 50′ 53.3″ S, 166° 45′ 37.5″ E	<1 year	Soil sampling	10
	Scott Base to McMurdo Station track	77° 50′ 50.6″ S, 166° 44′ 52.0″ E	Still in use	Walking track	600
	Crater Hill Summit lower track and IR7 site (2)	77° 50′ 38.7″ S, 166° 45′ 14.3″ E	Still in use	Walking track	700
	Active layer disturbance site (cut and fill site)	77° 50′ 53.9″ S, 166° 45′ 42.7″ E	19 years	Bulldozer cut/fill	50
	Williams Field to McMurdo Pipeline	77° 50′ 40.1″ S, 166° 45′ 09.9″ E	19 years	Re-contouring	1000
	Telecom cable site	77° 50′ 48.9″ S, 166° 45′ 11.7″ E	19 years	Bulldozer cut	300
	Up Observation Hill Track	77° 51′ 04.5″ S, 166° 41′ 24.6″ E	Still in use	Walking track	400
	Round Observation Hill Track	77° 51′ 07.7″ S, 166° 42′ 19.0″ E	Still in use	Walking track	500
	Crater Hill site A	77° 50′ 39.7″ S, 166° 43′ 32.7″ E	<1 year	Bulldozer cut	100
	Crater Hill site B	77° 50′ 48.2″ S, 166° 42′ 50.6″ E	16 years	Bulldozer cut	100
	Crater Hill site C	77° 50′ 31.3″ S, 166° 42′ 53.2″ E	40–50 years	Bulldozer cut	100
Cape Evans	Wind Vane Hill Track	77° 38′ 13.1″ S, 166° 25′ 09.3″ E	Still in use	Walking track	200
	Former Greenpeace World Park Base	77° 38′ 05.2″ S, 166° 25′ 20.6″ E	18 years	Station	8000
Marble Point	North of experimental concrete mound	77° 26′ 12.5″ S, 163° 47′ 58.4″ E	40–50 years	Bulldozer cut	10
	57/58 road to tarsealed exp. Mound	77° 25′ 41.4″ S, 163° 44′ 24.9″ E	40–50 years	Vehicle track	1000
	Subsidiary present day vehicle track	77° 26′ 12.7″ S, 163° 47′ 47.9″ E	Still in use	Vehicle track	1000
	Main present day vehicle track	77° 26′ 12.9″ S, 163° 47′ 46.9″ E	Still in use	Vehicle track	1000
	Bulldozed hummocky ground, ice-cored moraine	77° 26′ 12.8″ S, 163° 48′ 03.8″ E	40–50 years	Bulldozer fill	100
	Raised beach sequence – bulldozed sites (3)	77° 25′ 36.0″ S, 163° 44′ 43.0″ E	40–50 years	Bulldozer compacted	200

Table 4 (*continued*)

Location	Site description	GPS location	Time since last disturbance	Cause of disturbance	Disturbed area (m^2)
	K123 Borehole site, Gneiss Point	77° 14′ 39.8″ S, 163° 26′ 14.8″ E	<1 year	Borehole installation/ maintenance	6
	Experimental pit site adj to c.'57/58 track	77° 25′ 50.1″ S, 163° 44′ 25.5″ E	40–50 years	Bulldozed pit	10
	57/58 bulldozer cut track	77° 25′ 50.2″ S, 163° 44′ 27.5″ E	40–50 years	Bulldozer cut	800
	57/58 CampSite, removed late 70s	77° 25′ 13.1″ S, 163° 41′ 04.5″ E	20–30 years	Campsite	100
	K123 soil climate station	77° 25′ 10.4″ S, 163° 40′ 56.6″ E	<1 year	Climate station installation/maintenance	6
	Bulldozer mounds near artificial lake	77° 25′ 09.9″ S, 163° 40′ 39.0″ E	40–50 years	Bulldozer fill	100
	Edge of bulldozed track across wetland	77° 25′ 19.2″ S, 163° 41′ 27.4″ E	40–50 years	Bulldozer cut	100
	Explosion pit, 800 m NE refuelling station, Gneiss Point	77° 24′ 33.2″ S, 163° 41′ 35.4″ E	40–50 years	Bulldozed pit	10
	Debris of Jamesway, 57/58 Camp, bulldozed late 70s	77° 25′ 13.3″ S, 163° 41′ 05.0″ E	20–30 years	Campsite	100
	57/58 CampSite, removed Jamesway site (#2)	77° 25′ 12.8″ S, 163° 41′ 02.4″ E	20–30 years	Campsite	100
	Fire site from late 70s clean-up	77° 25′ 07.8″ S, 163° 40′ 53.9″ E	20–30 years	Campsite	4
Taylor Valley	Taylor Valley Visitor Zone (TVVZ), walking tracks	77° 37′ 35.3″ S, 163° 03′ 18.6″ E	<1 year	Walking track	600
	TVVZ, moist soft sand-rich till near pro-glacier lake	77° 07′ 04.4″ S, 163° 02′ 48.3″ E	<1 year	Pristine site	600
Wright Valley	K123 Loop moraine campsite & tracks (3)	77° 29′ 10.8″ S, 162° 21′ 50.6″ E	5 years	Campsite, walking track	300
	K123 VXE6 Pond campsite	77° 33′ 47.6″ S, 161° 16′ 31.6″ E	3 years	Campsite	100
	Vanda Treading Trial site – Rocky site, Fan site (2)	77° 31′ 33.3″ S, 161° 41′ 28.3″ E	17 years	Treading trial/ walking track	100
	Former Vanda Station, central court area	77° 31′ 41.5″ S, 161° 40′ 18.6″ E	17 years	Station	8000
	Former Vanda Station "Grey Water" Gully	77° 31′ 42.0″ S, 161° 40′ 22.1″ E	17 years	Rubbish disposal	40
	Former Vanda Station, vehicle track to fuel store	77° 31′ 43.6″ S, 161° 40′ 10.0″ E	17 years	Vehicle track	1000
	Former Vanda Station, primary helo pad	77° 31′ 45.3″ S, 161° 40′ 03.4″ E	17 years	Former helo pad	100
	Former Vanda Station, vehicle track to 2nd helo pad	77° 31′ 46.3″ S, 161° 40′ 07.5″ E	17 years	Vehicle track	1000
	Bull Pass refuge hut to seismic hut track	77° 31′ 04.2″ S, 161° 51′ 09.1″ E	<1 year	Walking track	150
	Bull Pass bedrock borehole site	77° 31′ 05.6″ S, 161° 51′ 04.1″ E	<1 year	Borehole installation/ maintenance	6
	Bull Pass soil climate station	77° 31′ 05.6″ S, 161° 51′ 04.1″ E	<1 year	Climate station installation/maintenance	6
Cape Roberts	Cape Roberts 1993 baseline VSA – southern & northern plots (2)	77° 02′ 07.3″ S, 163° 10′ 43.0″ E	10 years	Soil sampling, vehicle/ walking tracks	1500

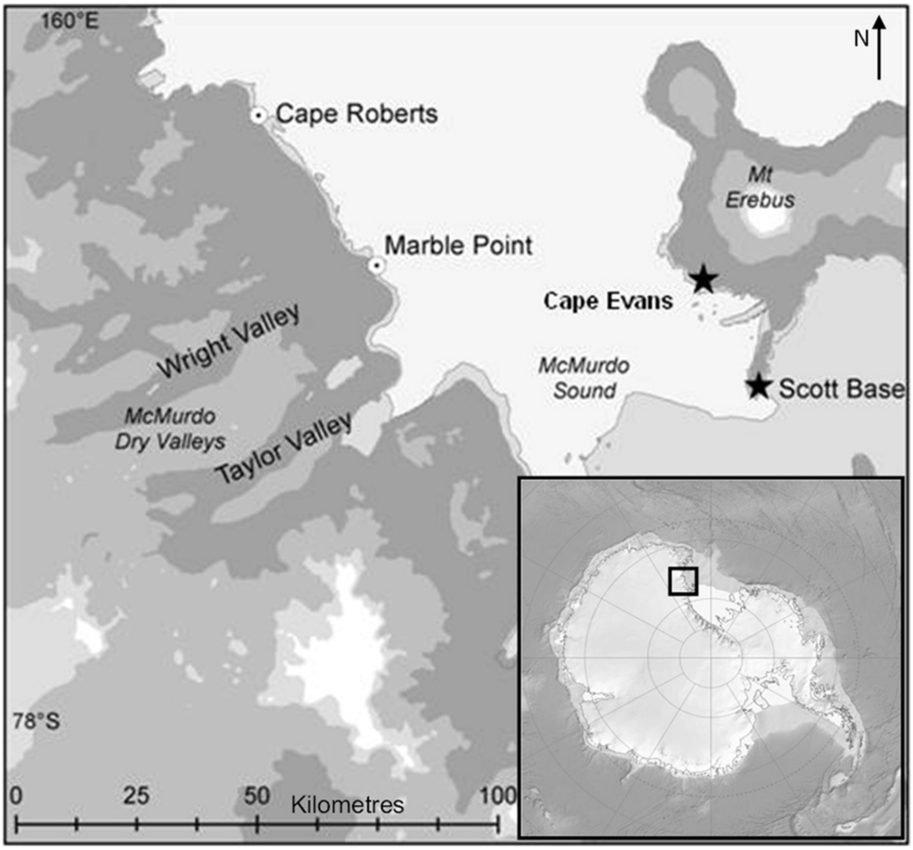

Fig. 4. Location of Ross Sea region study sites.

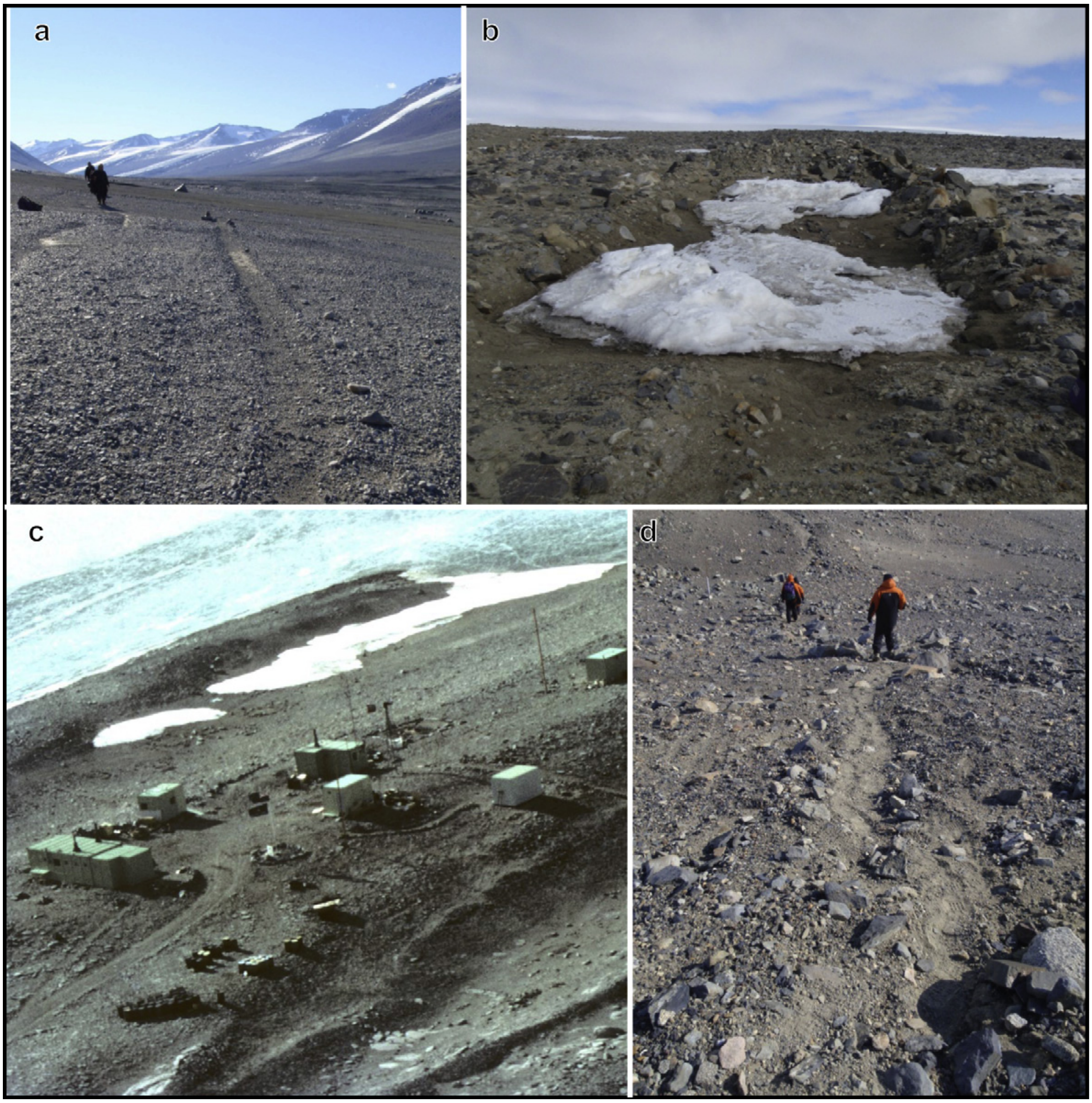

Fig. 5. Examples of disturbed sites investigated. a) Vanda experimental treading trial site, Wright Valley; b) bulldozed pit, Marble Point; c) Former Vanda Station site, Wright Valley c. 1972. Photo: Mike Wing; d) A walking track in the Taylor Valley Visitor Zone, McMurdo Dry Valleys.

removed clasts, 5–10 cm in diameter, were still evident at the Telecom Cable site and the Williams Field to McMurdo Station pipeline site, 19 years after the disturbance took place. Salt veneers on the underside of surface clasts are common in some Ross Sea region settings, making fresh overturns clearly visible compared to the surrounding undisturbed pavement surfaces. Without remediation, and replacing overturned clasts to their original salt-side-down positions and orientations, overturned clasts remain an obvious feature on a disturbed surface. A succession of increasingly armoured desert pavements was apparent in the chronosequence of disturbance skirting Crater Hill near Scott Base (Table 6). Each Crater Hill site, Crater Hill site A, B, and C, comprised scoriaceous basalt parent material, and each was disturbed by bulldozers (active layer removal for roading/fill material). Thus, amongst the Crater Hill succession of sites, time since disturbance was the main variable. The effect of time since disturbance is reflected in the MRIs for the Crater Hill succession: Crater Hill site C, >40 years since last disturbance, MRI = 100%, Crater Hill site B, intermediate aged disturbance and intermediate stage of recovery, MRI = 66%, and Crater Hill site A, <one year since last disturbance, highly disturbed, and MRI = 23% (Table 6).

In many Ross Sea region landscapes there is a marked colour contrast between the highly weathered surface soil material and the less weathered subsurface (Campbell et al., 1998b). Upon disturbance, paler, unweathered, and/or fine textured soil material is exposed at the surface. Surface colour contrast consistently showed the greatest difference amongst the sites disturbed >30–40 years prior to investigation, with geotechnical explosion pit sites at Marble Point, for example, still showing a strong colour contrast more than 40 years after the original disturbance.

The desert pavement recovery criteria that were least commonly identified in the 54 sites in this study were: the degree of surface clast weathering (recovery criteria III); salt accumulation on the underside a clasts (V); evidence of subsidence and melt-out (IX); and patterned ground development (XI).

The degree of surface clast weathering is an important consideration on desert pavement surfaces that have weathering stages 3 through to 6, where a visible difference between a newly disturbed

Table 5
Site description, parent material, soil classification, soil climatic zone, Ross Sea region climatic zone, weathering stage, salt stage, and mean depth to permafrost of the sites.

General location	Site description	Parent material	Soil classification[a]	Soil climatic zone[b]	Ross Sea region climatic zone[c]	Wxg stage[d]	Salt stage[e]	Depth to permafrost
Scott Base	Tracks in the vicinity of Scott Base and McMurdo Station, active layer disturbance site, Crater Hill windfarm sites	Scoriaceous basalt	Typic Haplorthel	Oceanic subxerous	Moist coastal mountain	1	1	32 cm[f]
Cape Evans	Wind Vane Hill Track and former Greenpeace World Park Base station	Scoriaceous basalt	Typic Haplorthel	Oceanic subxerous	Moist coastal mountain	1	1	50 cm[g]
Marble Point	1957/58 vehicle tracks, campsite, experimental tarmac and geotechnical investigation sites, present day vehicle tracks, K123 climate station and boreshole sites	Marble dominated till with granite, dolerite, sandstone and gneiss	Typic Anhyorthel, Calcic, Typic Haplorthel	Oceanic subxerous	Moist coastal mountain	1,2	1	49 cm[f]
Taylor Valley	Taylor Valley Visitor Zone tracks and lookout	Mixed till of gneiss and grano-diorite origin	Lithic Anhyorthel	Xerous	Central mountain	2	1	45 cm[g]
Wright Valley	K123 campsites and tracks, Former Vanda Station sites, treading trial sites,	Colluvium comprising mixed till of grano-diorite origin, fractured grano-diorite, grano-diorite-lamprophyte sands	Typic, Lithic Anhyorthel	Xerous	Central mountain	1,2	1	45 cm[g]
	Bull Pass tracks, climate station, and borehole sites	Aeolian sands of granite dominated mixed till origin	Typic Anhyorthel	Xerous	Central mountain	2	1	46 cm[f]
Cape Roberts	Cape Roberts Drilling Project sites	Beach gravels and grano-diorite bedrock	Typic Haploturbel Typic, Lithic Haplorthel	Oceanic subxerous	Moist coastal mountain	1	0,1	60 cm[g]

[a] Soil classification *after* Soil Survey Staff (2002).
[b] Soil climatic zones *after* Campbell and Claridge (1987).
[c] Ross Sea region climatic zones *after* Campbell and Claridge (1987).
[d] Soil weathering stage *after* Campbell and Claridge (1975).
[e] Soil salt stage *after* Bockheim (1997).
[f] Depth to permafrost from Adlam et al. (2010).
[g] Depth to permafrost estimated by authors from knowledge of climate at site and active layer depth in neighbouring similar areas.

Table 6
Desert Pavement Recovery criteria and Mean Recovery Index (MRI) for disturbed sites (in bold), and adjacent control sites (unbolded) at Scott Base and Marble Point.

Site	Time since disturbance	Desert Pavement Recovery criteria											MRI (%)
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
Scott Base													
Scott Base Microbial Experiment site	<1 year	**2**	**2**	**2**	**1.5**	**4**	**3**	**1.5**	**3**	**3**	**4**	**0**	**74**
		3	4	2	2	4	3	2	3	3	4	0	
Scott Base-McMurdo Station Track	Still in use	**1**	**1**	**2.5**	**2**	**3**	**1**	**2**	**2**	**3**	**4**	**2**	**76**
		3	3.5	2.5	3	3	1	3	4	3	4	2.5	
Crater Hill Summit lower Track	Still in use	**1**	**1**	**1.5**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**	**72**
		2.5	3	1.5	2.5	1	1	2	4	2	2	1	
Crater Hill Summit Track (IR7 site)	Still in use	**1**	**2**	**2**	**1**	**1**	**2**	**1**	**1**	**3**	**1**	**1**	**71**
		3	4	2	1	1	3	2	4	3	1	2	
Active layer disturbance site (cut site)	19 years	**3**	**4**	**1**	**1**	**4**	**2.5**	**4**	**2**	**0**	**1**	**4**	**71**
		4	4	1	3	4	3	4	4	4	3	4	
Active layer disturbance site (fill site)	19 years	**3**	**4**	**1**	**1**	**4**	**3**	**4**	**2**	**4**	**4**	**4**	**83**
		4	4	1	3	4	3	4	4	4	3	4	
Williams Field to McMurdo Pipeline	19 years	**2**	**2**	**1**	**2**	**0.5**	**0.5**	**0**	**0**	**2**	**2**	**0**	**54**
		2.5	3	1.5	2.5	1	1	2	4	2	2	1	
Telecom cable site	19 years	**0.5**	**2**	**1**	**1**	**2**	**2**	**0.5**	**1**	**2**	**3**	**0**	**59**
		3	4	2	2	4	3	2	2	1	1	2	
Up Observation Hill Track	Still in use	**1**	**2**	**1**	**0**	**0**	**0**	**2**	**1**	**4**	**4**	**0**	**71**
		2	4	1	3	0	0	4	4	4	4	0	
Round Observation Hill Track	Still in use	**2**	**2**	**1**	**0**	**0**	**0**	**1**	**2**	**4**	**3**	**4**	**73**
		3	4	1	4	0	0	3	4	4	3	0	
Crater Hill site A	<1 year	**0**	**1**	**0**	**0**	**0**	**3**	**0**	**0**	**1**	**0**	**0**	**23**
		3	4	2.5	4	4	3	3	4	4	4	0	
Crater Hill site B	16 years	**2**	**3**	**2**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**0**	**66**
		3	4	2.5	4	4	3	3	4	4	4	0	
Crater Hill site C	40–50 years	**3**	**4**	**2.5**	**4**	**4**	**3**	**3**	**4**	**4**	**4**	**0**	**100**
		3	4	2.5	4	4	3	3	4	4	4	0	
Marble Point													
North of experimental concrete mound	40–50 years	**4**	**4**	**2**	**4**	**3**	**2**	**2.5**	**2**	**4**	**4**	**0**	**91**
		4	4	2	4	3	2	2.5	4	4	4	2	

(*continued on next page*)

Table 6 (*continued*)

Site	Time since disturbance	Desert Pavement Recovery criteria											MRI (%)
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
57/58 road to tarsealed exp. mound	40–50 years	**3**	**4**	**2**	**3**	**2**	**1**	**3**	**2**	**4**	**4**	**0**	**96**
		3	4	2	3	2	1	3	4	4	4	0	
Subsidiary present day vehicle track	Still in use	**2**	**4**	**2.5**	**3**	**3**	**1**	**2**	**2**	**4**	**4**	**0**	**89**
		3	4	2.5	4	3	1	3	4	4	4	0	
Main present day vehicle track	<1 year	**2**	**4**	**1**	**3**	**0**	**0**	**2.5**	**2**	**4**	**3**	**0**	**80**
		2	4	1	4	0	0	2.5	4	4	3	2	
Bulldozed, ice-cored moraine	40–50 years	**4**	**4**	**1**	**3**	**0**	**0**	**2.5**	**4**	**0**	**2**	**0**	**75**
		4	4	1	4	0	0	2.5	4	4	4	2	
Raised beach sequence (compacted site)	40–50 years	**2**	**4**	**1**	**3.5**	**2**	**1**	**1.5**	**2**	**4**	**4**	**0**	**78**
		4	4	1	4	2	1	2	4	4	4	2	
Raised beach sequence (cut site)	40–50 years	4	**4**	**1**	**4**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**70**
		4	4	1	4	2	1	2	4	0	0	2	
Raised beach sequence (winrow)	40–50 years	**3**	**4**	**1**	**3.5**	**1**	**0.5**	**2**	**2**	**4**	**0**	**2**	**83**
		4	4	1	4	2	1	2	4	4	0	2	
Borehole site, Gneiss Point	<1 year	**4**	**3**	**3**	**4**	**0**	**0**	**0**	**0**	**4**	**4**	**0**	**94**
		4	4	3	4	0	0	0	0	4	4	0	
Experimental pit site adj to '57/58 track	40–50 years	**2**	**4**	**2**	**0**	**0**	**1**	**2**	**2**	**1**	**2**	**0**	**48**
		4	4	2	4	3	2	2	4	4	4	2	
57/58 bulldozer cut track	40–50 years	**3**	**4**	**2**	**4**	**1**	**1**	**1**	**1**	**4**	**4**	**1**	**65**
		4	4	2	4	3	2	2	4	4	4	2	
57/58 CampSite, removed late 70s	20–30 years	**2**	**4**	**1**	**1**	**0**	**1**	**1**	**1**	**1**	**2**	**0**	**51**
		4	4	1	4	4	2	3	4	4	4	0	
K123 soil climate station	<1 year	**2**	**4**	**1**	**3**	**2**	**2**	**3**	**4**	**4**	**4**	**0**	**89**
		4	4	1	4	4	2	3	4	0	0	0	
Bulldozer mounds near artificial lake	40–50 years	**2**	**4**	**1**	**1**	**4**	**1**	**3**	**4**	**4**	**2**	**4**	**83**
		4	4	1	3	4	1	4	4	4	4	4	
Edge of bulldozed track across wetland	40–50 years	**4**	**4**	**1**	**4**	**0**	**0**	**3**	**4**	**4**	**0**	**0**	**98**
		4	4	1	4	0	0	4	4	4	0	0	
Explosion pit, 800 m NE refuelling station	40–50 years	**2**	**4**	**2.5**	**0**	**1**	**1**	**3**	**1**	**0**	**0**	**1**	**45**
		3.5	4	2.5	4	3.5	2	3	4	4	4	4	
Debris of bulldozed Jamesway, '57/58 Camp	20–30 years	**1.5**	**4**	**1**	**0**	**1**	**1**	**2**	**1**	**0**	**2**	**0**	**50**
		4	4	1	4	4	2	3	4	4	4	0	
57/58 CampSite, removed Jamesway (#2)	20–30 years	**1**	**4**	**1**	**1**	**1**	**1**	**3**	**2**	**1**	**1**	**0**	**57**
		4	4	1	4	4	2	3	4	4	4	0	
Fire site from late 70s clean-up	20–30 years	**2.5**	**4**	**1**	**3**	**4**	**2**	**2**	**1**	**3**	**0**	**0**	**80**
		4	4	1	4	4	2	3	4	4	4	0	

Desert Pavement Recovery criteria: I = embeddedness of surface clasts; II = impressions of removed clasts; III = degree of clast surface weathering; IV = % overturned clasts; V = salt on underside of clasts; VI = development of salt coatings; VII = armouring per 1 m^2; VIII = colour contrast; IX = evidence of subsidence/melt out; X = accumulation of salt on cut surfaces; XI = patterned ground development.

surface and a highly ventifacted and pitted desert pavement would be obvious. We were unable to include examples of older, higher elevation, weathering stage 3–6 sites in this study. Salt accumulation on the underside of clasts is also expected to be more useful when older surfaces are investigated, because as soil development increases, salt encrustations become thicker, and can therefore be a good indication of desert pavement maturity, and disturbance. Subsidence, melt-out, and patterned ground development are potentially useful indicators of desert pavement disturbance and recovery only where large-scale bulldozer removal of active layer material has occurred. Only 10 sites out of the 54 sites in this study included large-scale bulldozer activity.

5.2. *Factors influencing desert pavement recovery*

The cold desert conditions, coupled with factors such as the absence of vegetative cover, scarcity of water, and minimal rate of natural movement of soil materials, inevitably slow soil recovery

Table 7
Desert Pavement Recovery criteria and Mean Recovery Index (MRI) for disturbed sites (in bold) and adjacent control sites (unbolded) at Taylor Valley, Wright Valley, Cape Evans, and Cape Roberts.

Site	Time since disturbance	Desert Pavement Recovery criteria											MRI (%)
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
Taylor Valley													
Taylor Valley Visitor Zone (TVVZ), lower track	<1 year	**1**	**4**	**2.5**	**1**	**3**	**1.5**	**3**	**1**	**4**	**0**	**3**	**76**
		3	4	2.5	4	4	1.5	4	4	4	4	3	
TVVZ, hilltop lookout	<1 year	**2**	**2**	**2.5**	**2.5**	**4**	**2**	**3**	**1**	**4**	**4**	**0**	**71**
		3	4	2.5	4	4	2	4	4	4	4	4	
TVVZ, steep track to head of Canada Glacier	<1 year	**0**	**1**	**2.5**	**0**	**0**	**0**	**0**	**0**	**4**	**4**	**0**	**39**
		3	4	2.5	4	4	2	3.5	4	4	4	3	
TVVZ, moist soft sand-rich till near pro-glacier lake	<1 year	**4**	**4**	**2**	**4**	**0**	**0**	**3**	**4**	**4**	**4**	**0**	**100**
		4	4	2	4	0	0	3	4	4	4	0	
Wright Valley													
K123 Loop moraine campsite, track to sampling site	5 years	**3**	**4**	**2**	**4**	**0**	**0**	**3**	**3**	**4**	**4**	**0**	**93**
		4	4	2	4	0	0	4	4	4	4	0	
K123 Loop moraine campsite, tent site	5 years	**4**	**4**	**2**	**4**	**0**	**0**	**4**	**4**	**4**	**4**	**0**	**100**
		4	4	2	4	0	0	4	4	4	4	0	

Table 7 (*continued*)

Site	Time since disturbance	Desert Pavement Recovery criteria											MRI (%)
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
K123 Loop moraine campsite, toilet track	5 years	**2**	**4**	**2**	**2**	**0**	**0**	**2**	**1**	**4**	**4**	**0**	**82**
		4	4	2	4	0	0	4	4	4	4	0	
K123 VXE6 Pond, campsite	3 years	**3**	**3**	**2.5**	**4**	**3**	**1**	**3**	**4**	**4**	**4**	**0**	**98**
		3	4	2.5	4	3	1	3	4	4	4	0	
Vanda Rocky Treading Trial site	17 years	**3**	**4**	**1.5**	**3**	**2**	**1**	**2**	**3**	**4**	**0**	**0**	**96**
		4	4	1.5	3	2	1	2	4	4	0	0	
Vanda Fan Treading Trial site	17 years	**2**	**4**	**2.5**	**1**	**0**	**1**	**2**	**1**	**4**	**0**	**0**	**62**
		3	4	2.5	4	1	1	3	4	4	0	3	
Former Vanda Station, central court area	17 years	**3**	**4**	**1**	**4**	**0**	**0**	**4**	**2**	**4**	**0**	**0**	**90**
		3.5	4	2	4	0	0	4	4	4	0	0	
Former Vanda Station "Grey Water" Gully	17 years	**3**	**4**	**1.5**	**4**	**0**	**0**	**1**	**4**	**4**	**4**	**0**	**95**
		3	4	1.5	4	0	0	2	4	4	4	0	
Former Vanda Station, track to fuel store	17 years	**1.5**	**4**	**2**	**1**	**0**	**0**	**2.5**	**3**	**4**	**4**	**0**	**87**
		2	4	2	3	0	0	3	4	4	4	0	
Former Vanda Station, primary helo pad	17 years	**2**	**4**	**1**	**4**	**0**	**0**	**2.5**	**3.5**	**4**	**4**	**0**	**97**
		2	4	1	4	0	0	3	4	4	4	0	
Former Vanda Station, vehicle track to 2nd helo pad	17 years	**3**	**4**	**0.5**	**4**	**0**	**0**	**3**	**3.5**	**4**	**4**	**0**	**99**
		3	4	0.5	4	0	0	3	4	4	4	0	
Bull Pass refuge hut to seismic hut track	<1 year	**1**	**1**	**1.5**	**0**	**0**	**0**	**3**	**3**	**4**	**4**	**0**	**85**
		3	4	1.5	0	0	0	3	4	4	4	0	
Bull Pass bedrock borehole site	<1 year	**3**	**4**	**2**	**4**	**0**	**0**	**2**	**4**	**4**	**4**	**0**	**98**
		4	4	2	4	0	0	2	4	4	4	0	
Bull Pass soil climate station	<1 year	**4**	**4**	**2**	**4**	**0**	**0**	**2**	**4**	**4**	**4**	**0**	**99**
		4	4	2	4	0	0	2	3.5	4	4	0	
Cape Evans													
Wind Vane Hill Track	Still in use	**2**	**3.5**	**1**	**3**	**4**	**1**	**3**	**1**	**4**	**2**	**0**	80
		3	4	1	4	4	1	4	1	4	4	0	
Former Greenpeace World Park Base	18 years	**1**	**4**	**1**	**4**	**0**	**0**	**3**	**4**	**4**	**4**	**0**	100
		1	4	1	4	0	0	3	4	4	4	0	
Cape Roberts													
Cape Roberts 1993 baseline VSA, southern plot	10 years	**2**	**4**	**1**	**3**	**0**	**0**	**1**	**2**	**4**	**3**	**0**	91
		2	4	1	3	0	0	2	4	4	3	0	
Cape Roberts 1993 baseline VSA, northern plot	10 years	**3**	**3**	**1**	**3**	**0**	**0**	**2**	**3**	**4**	**4**	**0**	88
		4	4	1	4	0	0	3	4	4	4	0	

Desert Pavement Recovery criteria: I = embeddedness of surface clasts; II = impressions of removed clasts; III = degree of clast surface weathering; IV = % overturned clasts; V = salt on underside of clasts; VI = development of salt coatings; VII = armouring per 1 m^2; VIII = colour contrast; IX = evidence of subsidence/melt out; X = accumulation of salt on cut surfaces; XI = patterned ground development.

rates in the Ross Sea region of Antarctica (Campbell et al., 1993, 1998a). The rate and extent of desert pavement recovery at the sites investigated could be attributed to a combination of the intensity of the initial disturbance; the environmental conditions for the site, including, parent material and surface characteristics (age and weathering stage), availability of water and wind regime; and also the restoration and remediation measures undertaken at the site.

Fig. 6. Crater Hill site A. Mean Recovery Index = 23%. Note lack of clast embeddedness, desert pavement armouring, high% overturned clasts, and accumulation of salt on the newly disturbed surface.

Fig. 7. Steep walking track at the Taylor Valley Visitor Zone. Mean Recovery Index = 39%. Note lack of clast embeddedness, moderate% overturned clasts, impressions of removed clasts, and colour contrast between walking track and adjacent undisturbed material. Arrows indicate fresh footprints. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This study assessed a range of sites disturbed at different times and by different intensities of human activity. The visible evidence of historic disturbances around Vanda Station and Marble Point (areas frequently visited over the last two decades by one of the authors) are limited to high intensity disturbances, such as bulldozed areas. Sites associated with high intensity disturbances, where the active layer has been disturbed and/or removed, subsurface soil material displaced, side-mounds formed by bulldozers, or where there are a high proportion of overturned clasts, had the lowest MRIs and disturbance had a lasting visible impact. The once widespread minor disturbances, such as footprints, which would have been widespread around the former Vanda Station and the old Marble Point camp, have recovered to be indistinguishable from the surrounding undisturbed material.

Wind is likely to be the primary driver of desert pavement recovery in most environments in the Ross Sea region (Bockheim, 2010; Campbell et al., 1998a). We assume wind action in valley floors and low ridge sites, such as the Loop Moraine, former Vanda Station, Vanda experimental treading trial sites, and the Taylor Valley Visitor Zone sites in the McMurdo Dry Valleys, assisted in the rehabilitation of the desert pavement. At most sites wind is likely to be the instigator in the first stages of formation of an incipient desert pavement following disturbance. In instances where we had records of low level disturbance, such as impacts from the tent sites at the Loop Moraine field site in the Wright Valley, wind action is likely to have resulted in natural infilling of footprints, sorting of surface materials to re-create the surface armouring of coarser material, and thus recovery of randomly trampled areas. Wind action, however, was not sufficient to redistribute larger clasts that lined the margins of several disturbed sites, such as the Loop Moraine walking-tracks, Marble Point bulldozer tracks, or diffuse the "indentation" visible across the walking tracks at the Loop Moraine and the Vanda Fan treading trial site.

The intermittent supply of moisture may have assisted in desert pavement recovery at some of the study sites. Disturbances occurring in the moist coastal climatic zones of Marble Point, the vicinity of Scott Base, Cape Evans, and Cape Roberts, are moistened by occasional summer snowfalls and spring snow thaw. Subsequent repetitive freeze–thaw action may have also aided recovery, and over time, jostled surface clasts into a more embedded position in the desert pavement surface and along with windblown material infilled the impressions of removed clasts. In the drier, central mountain climatic zones, such as the McMurdo Dry Valleys, further from the coast, moisture available for soil surface processes is less, and recovery was generally not as advanced as equivalent intensity disturbances in moister areas.

Campbell et al. (1998a,b) and O'Neill (2012) showed that initial physical disturbance in the landscape is greatest where there was a fine-textured gravel, sand, and pebble pavement and the soils had a low proportion of coarse materials. However, this study has shown in spite of seemingly rapid initial disturbance and obvious visible damage, finer textured desert pavements can undergo rapid rehabilitation under favourable conditions (high moisture and/or wind regime). In many cases the least disturbance and greatest recovery was observed where the desert pavement was predominately boulders and cobbles, as the hardy nature of the surface material, such as the weakly weathered, slabby grano-diorite comprising the former Vanda Station site, showed little evidence of the once widespread trampling and vehicle tracks which would have criss-crossed this area. It is evident that many vehicle and walking tracks developed around the stations and campsites are not preserved as they were on resilient or rocky, parent materials. The ability to recognise young active surfaces, such as active beach deposits, and sand dunes, where material is readily reorganised by wind or water, is important, as in these settings the initial damage may seem high, but the ability of surfaces to recover is greater than some older less resilient landforms and parent materials.

5.3. *Site remediation*

Site remediation (raking and smoothing of disturbed surfaces to free-up compacted soil, and redistribute out of place stones) was effective, where surface materials were not strongly weathered (weathering stage 1 or 2), and led to accelerated visual recovery of the desert pavement at 11 of the sites studied. Ten years after remediation both of the Cape Roberts study sites were nearly indistinguishable from equivalent control sites (Northern Plot MRI = 88%, Southern Plot MRI = 91%), with no obvious evidence of vehicle traffic or human traffic disturbances. Furthermore, the redistribution of disturbed rocks from vehicle and walking track margins at the former Vanda Station site (MRI = 90%), was effective at reducing visible disturbance and aiding surface pavement recovery. Surface restoration is only a cosmetic effect as the subsurface material, such as an infilled soil pit, remains permanently disturbed.

5.4. *Recommendations for future research*

The Desert Pavement Recovery Assessment method was formulated as a simple, reproducible method that gives semi-quantitative results for assessing the physical recovery of a site following disturbance. The method was designed to be

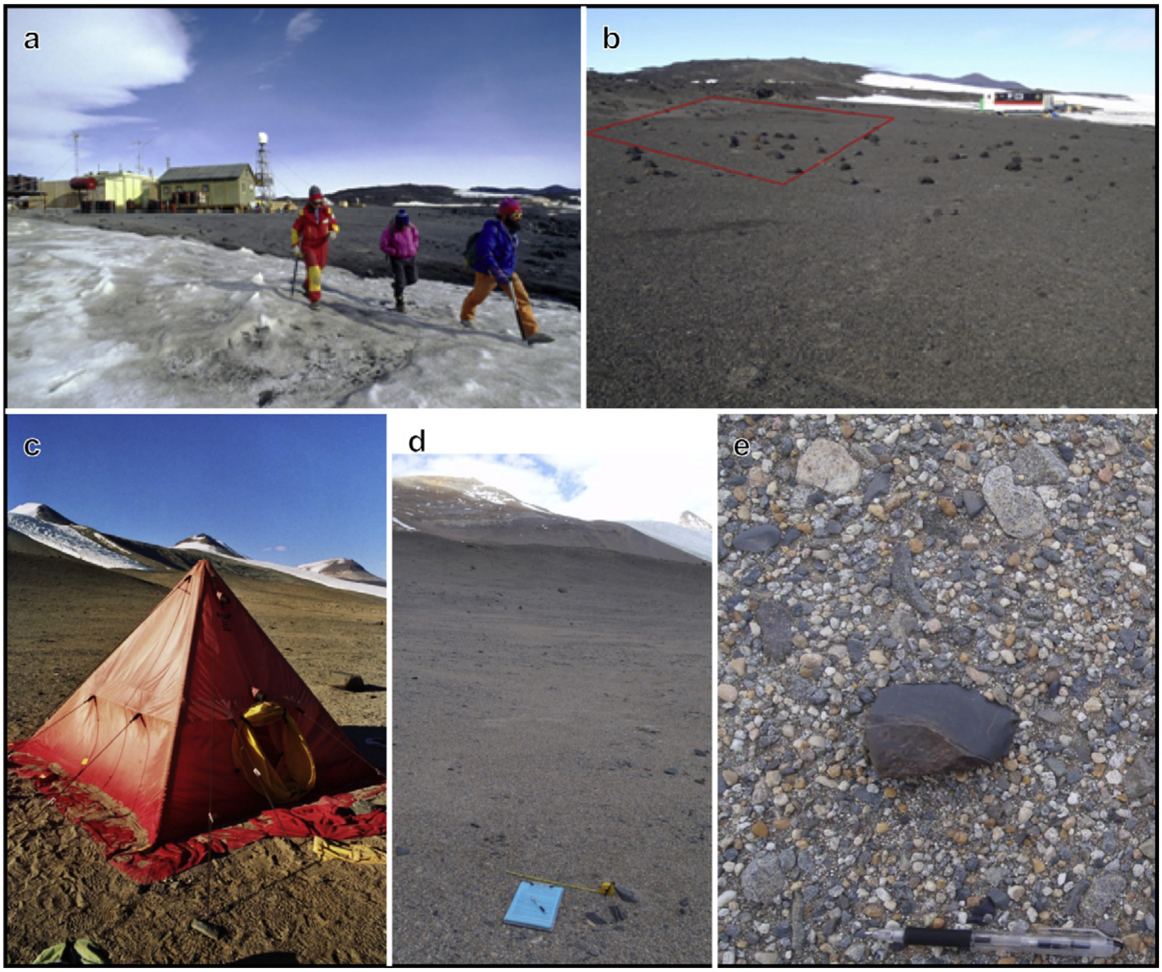

Fig. 8. Examples of sites showing the greatest desert pavement recovery. Greenpeace World Park Base at Cape Evans. a) Greenpeace huts and fuel storage racks in Jan. 1992; b) red rectangle marking the location of the former Greenpeace base, Jan. 2009, Mean Recovery Index = 100%. Site of the Loop Moraine campsite, tent site. c) Loop Moraine tent site, Dec. 2004. Photo: Fiona Shanhun; d) Loop Moraine tent site, 5-years later, Dec. 2009; e) Desert pavement at the Loop Moraine tent site, Dec. 2009, Mean Recovery Index = 100%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

independent of the factors that influence landscape recovery so it could be used simply to determine whether a site had recovered or not, irrespective of time, parent material, and disturbance intensity. Investigation of a greater number of sites with a wider range of disturbance types, older sites of known low and moderate intensity disturbances, and older, highly weathered surfaces (weathering stages 3–6) are needed to develop the method for use as a predictive tool.

The Desert Pavement Recovery Assessment method described in this paper provides an addition to the range of tools available for environmental assessment and management in Antarctica. There is potential to extend the method to assess desert pavement recovery in other parts of the Antarctic continent and high Arctic environments. Future applications could be developed to combine field-based observations applying our Desert Pavement Recovery Assessment method with remotely sensed data, such as reflectance and soil texture density spatial data.

6. Conclusions

The Desert Pavement Recovery Assessment method presented here is a simple field-based method which was formulated and tested on a range of disturbed sites in the Ross Sea region of Antarctica in the austral summer of 2008/09 and 2009/10. The Desert Pavement Recovery Assessment method uses a set of recovery criteria developed to assess ground surface recovery from human disturbance. Assessed criteria were: embeddedness of surface clasts; impressions of removed clasts; degree of clast surface weathering; % overturned clasts; salt on underside of clasts; development of salt coatings; armouring per m^2; colour contrast; evidence of subsidence/melt out; accumulation of salt on cut surfaces; and evidence of patterned ground development. A method by which an overall *Mean Recovery Index* (MRI) can be calculated has been developed.

The method was tested on 54 sites including areas disturbed by: bulldozer scraping for road-fill, contouring for infrastructure, geotechnical investigations, and experimental treading trial sites. Disturbances had occurred at timescales ranging from one week to 50 years prior to assessment.

The extent of desert pavement recovery at the sites investigated in this study was higher than anticipated. Fifty of the 54 sites investigated were in an intermediate, or higher, stage of desert pavement recovery, 30 sites were in an advanced stage of recovery, and four sites were indistinguishable from adjacent control sites (MRI = 100%).

Five of the 11 recovery criteria proved the most useful in determining the *Mean Recovery Index* of the sites (embeddedness of surface clasts, impressions of removed clasts, % overturned clasts, armouring per m^2, and colour contrast between the disturbed and control desert pavement sites). The remainder, including salt accumulation on the underside of clasts, and the degree of surface clast weathering, are expected to be more useful when older surfaces are investigated.

Of the sites investigated, active surfaces, such as the gravel beach deposits, aeolian sand, and alluvial fan deposits, recovered relatively quickly, whereas less active sites of higher intensity disturbances, such as the bulldozed tracks at Marble Point, showed only intermediate recovery 20–30 years after disturbance. Desert pavements disturbed by randomly dispersed footprints, such as the temporary field campsites at the Loop Moraine, recovered to be undetectable (MRI = 100%) within five years, whereas track formation from repeated trampling, and consequently concentrating larger clasts along the margin of a confined track, persisted for over 15 years (MRI = 82%).

This study introduces a tool which can be used to advance environmental management in the Ross Sea region of Antarctica. Further investigation into older, highly weathered landscapes, and a greater number of sites impacted by low-to-moderate intensity disturbances is needed to further develop the method and allow it to be used as a predictive tool.

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