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Testing the validity of upslope migration in banded vegetation from south-west Niger

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Abstract

Recent studies of banded vegetation have suggested a successional model, in which bare bands are colonised in a pioneer front on the upslope side of a vegetation band. Vegetation patterns in south-west Niger have been interpreted to suggest that spatial transitions reflect this form of temporal succession, and in these patterns there is corroborating evidence for slow up-slope migration. However, given the inherent difficulties of long-term field experiments there are few data to judge the validity of this model. The use of the artificial radionuclide caesium-137 (^{137}Cs) to provide information on net soil flux over the past ca. 30 years offers potential in this regard. Furthermore, the identification of various types of soil crust, which can induce different types of hydrological behaviour, provides valuable information for predicting soil evolution. To test the hypothesis that banded vegetation migrates upslope, a 70-m transect encompassing two vegetation bands and a single bare lane was sampled in south-west Niger. The transect was aligned orthogonal to the bands and approximately parallel to the direction of water, soil and nutrient flow. Soil samples for gamma-ray spectrometry and particle-size analysis were collected along the transect at 21 locations with 1-m intervals in the lower part and three samples were obtained on the upper part. Prior to collection, the soil surface characteristics were examined to distinguish between crust types and to identify the presence of termite activity. The results demonstrate the utility of these techniques for examining the net redistribution of soil over a period of three decades and its relations to vegetation succession. The amount of soil eroded was found generally to decrease downslope, whilst the proportion of fine silt in the soil generally increased downslope. These patterns correspond with the location of the erosion and sedimentation crusts identified

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using a standardised classification. The relations between microtopography and net soil flux may also explain some of the spatial variation in soil redistribution processes. The intensity of crust and ^{137}Cs measurements on the upslope edge of the lower vegetation band enabled the calculation of the upslope migration rate (ca. 0.19–0.27 m yr^{-1}) which coincided with independent studies in the same region. However, because considerable spatial variations in topography and soil flux were found to occur over very small distances, further detailed studies over larger areas will be needed.

Keywords: Banded vegetation; South-west Niger; Caesium-137 (^{137}Cs); Soil erosion

1. Introduction

Stripes of vegetation and bare ground have been noted on aerial photographs at many places worldwide and several hypotheses have been proposed to explain their origin. The perpendicular alignment of vegetation arcs in Jordan and in Mali to the dominant wind has been interpreted as evidence for their association with aeolian transport (White, 1969; Leprun, 1992). However, detailed studies of the dynamics of vegetation bands in northern Mexico (Cornet et al., 1992; Montaña, 1992) were taken to suggest that their formation was related to surface wash. The second hypothesis is now widely accepted where low-frequency, high magnitude rainfall events produce runoff on slightly inclined slopes on which the soils have low permeability resulting from an abundance of fine particles (Cornet et al., 1992). In this environment, surface wash is generated in the bare patches between the bands but accumulates and infiltrates at their upslope edges, where the resulting soil moisture promotes plant colonisation. Furthermore, it is hypothesised that when plants colonise this zone, they gradually cut off the supply of water and nutrients to the rest of the band. Consequently, the whole band should move upslope (Thiery et al., 1995).

The runoff hypothesis is now also generally accepted as an explanation for the 'brousse tigrée' banded vegetation patterns of south-west Niger. Support for the hypothesis in this area has been provided by Thiery et al. (1995), who also showed a temporal succession of different crusts across the band and interband. These authors developed a model to simulate formation of the bands, which could generate a variety of patterns depending on varying rainfall and surface wash conditions. However, the dynamic operation of this model cannot be verified without difficult long-term studies. Early field evidence of band shifts mainly due to aeolian activity has been provided by Leprun (1992), working in Mali, where a bench-mark in 1955 was located within a band and 21 years later was found to be in a barren lane. The migration distance was apparently 15.8 m, resulting in a mean annual velocity of 0.75 m yr^{-1}. Other bench-marks in the same region indicated annual velocities ranging between 0.20 m yr^{-1} and 0.25 m yr^{-1} (Leprun, 1992).

Since soil redistribution is essential for the operation of the plant successional model, it is reasonable to assume that long-term monitoring of soil erosion would provide an indicator of band migration. Unfortunately, studies of contemporary soil erosion cannot give accurate estimates for periods long enough to cover the rate of band migration (Higgitt, 1991) especially in semi-arid environments with high spatial and temporal variability in rainfall. However, many of the problems with long-term monitoring of soil redistribution can be overcome by using the artificial radionuclide caesium-137 (^{137}Cs) to trace soil movement (Sutherland and de Jong, 1990). The ^{137}Cs technique provides accurate net soil flux measurements aggregated over the last ca. 30 years (Martz and de Jong, 1991) and has been used successfully in many environments throughout the world (Walling and Quine, 1992).

Thus, the aim here is to measure net soil flux in south-west Niger using ^{137}Cs and to relate it to surface features and transitions in the structure of the brousse tigrée in an attempt to validate the model and quantify the rate of upslope band migration.

2. Materials and methods

2.1. Study area

The study area is 70 km east of Niamey in south-west Niger. The climate is semi-arid with a monomodal rainfall distribution. The average rainfall at Niamey for the period 1905–1989 was about 560 mm (Lebel et al., 1992), but for the past 25 years the rainfall has been persistently below-average with a mean of about 495 mm. Potential evapotranspiration is approximately 2000 mm (Sivakumar, 1989).

During the summer, south-westerly winds are replaced periodically by easterly squalls with short-duration, high-intensity rainfall. The intense rainfall can cause crusting, clay eluviation and rapid removal of unconsolidated material from the surface (Casenave and Valentin, 1989). Strong winds precede many of the squalls, and these raise large quantities of dust. During the dry winter months, north-easterly winds of the Harmattan dominate, bringing dust from southern Sahara (McTainsh and Walker, 1982). Drees et al. (1993) reported a highly seasonal occurrence of dust deposition in Niger. They suggested that the frontal storms were responsible for more dust infall than was the Harmattan.

2.2. Banded vegetation structure, soil and hydrological processes

The brousse tigrée in this region occurs only on broad ironstone-capped plateaux with slopes generally lower than 0.3°. The parent material of soil on the plateaux is highly weathered, humus-poor and sesquioxide-rich. Clays are mostly kaolinitic. The soil is gravely loam over cemented ironstone gravel (Manu et al., 1991). It is acid (pH < 5), of low nutrient status and has little water storage capacity because of its shallow depth and large content of coarse fragments. The surface has bare patches interspersed with bands of vegetation of varying sizes, oriented with their long axis parallel to the contour (Thiery et al., 1995). The soil within the vegetation bands is different from that between the bands; pH is 5 to 6 and it is humus-rich, and approximately 20 cm thick above the ferricrete cobbles.

The brousse tigrée (band and interband) has been divided into five typical zones (Thiery et al., 1995), shown in Fig. 1. The central zone (C) in the figure has a dense (60–100%) canopy, small shrubs in the understorey and sparse grass cover. The soil has

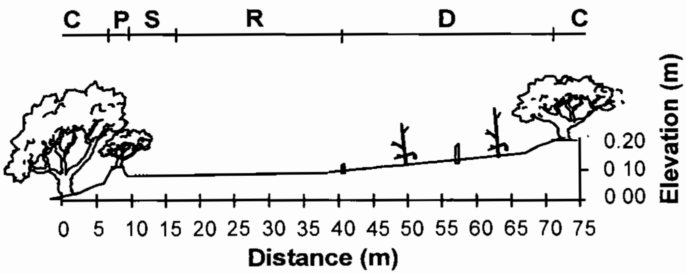

Fig. 1. Schematic cross-section of 'brousse tigrée' showing the typical zones, topography and the soil sample locations.

high porosity related mainly to termite activity. Surface crusts are virtually absent apart from a few remnants of 'sedimentary' crusts and 'erosion' crusts which are restricted to the vicinity of active termite mounds. The degraded zone (D) has low shrub cover (40–0%) and is dominated by 'structural sieving' crusts indicative of intensive impact of rainfall and sheetflow (Valentin and Bresson, 1992). The runoff zone (R) has no plant cover, but includes erosion and gravel crusts which produce intensive runoff. The sedimentation zone (S) is also devoid of vegetation with the exception of annual grasses in the lowest zones and is characterised by sedimentary crusts which spread over nearly the whole surface and cover old erosion and gravel crusts. The pioneer zone (P) comprises either a 'bay' or 'cape' structure in which the former has nearly total cover of annual grasses whilst the latter is predominantly colonised by *Guiera senegalensis*. In both situations the sedimentary crusts are almost entirely destroyed by plant emergence and termite activity.

2.3. Sampling and laboratory analyses

Soil samples and in situ soil crust observations were collected at 24 sites in March, 1995 along a transect aligned orthogonal to the orientation of the vegetated bands (Fig. 1). In the lower part of the transect samples were collected at 21 locations with 1 m intervals because variation in sedimentation rates were thought to be more variable here, whilst only three samples were obtained on the upper part. Samples were taken from small pits (0.01 m^2) to a depth which varied with contact to ironstone cobbles. Each sample was weighed, homogenised and subsampled to provide a representative sample of the soil profile and then re-weighed.

The particle-size distribution was determined by a Malvern 2600 laser sizer on subsamples with the organic matter removed prior to ultrasonic disaggregation. The threshold values for percentage clay, silt and sand content used in subsequent analyses are 2 μm, 60 μm and 1128 μm.

The ^{137}Cs activity was measured by gamma-ray energy spectrometry. The soil samples were prepared by air-drying and grinding with mortar and pestle to pass a 1-mm sieve. The samples were placed in a standard Marinelli (re-entrant) beaker which was then located on a horizontally-oriented 20% relative efficiency hyper-pure germanium (HpGe) gamma-ray detector. The detector was coupled to spectroscopy-grade amplifiers and a PC-based data collection system. Calibration samples were used to derive the absolute ^{137}Cs activities in each sample.

2.4. Calculation of net soil flux from ^{137}Cs

The ^{137}Cs concentration in the soil of the plateau is ten times greater than at other locations in this region (Chappell, 1995). It is thought that the preferential accumulation of ^{137}Cs-enriched dust beneath vegetation on the plateau is responsible, thus making it difficult to identify a 'stable' ^{137}Cs reference site (Chappell, 1995). Because of this the site chosen as the reference was devoid of vegetation except for a layer of annual grasses, close to the study area, where there has been no cultivation or wood cutting for at least ca. 30 years, and where only limited erosion is likely to have taken place. A mass-specific exponential model was fitted to the ^{137}Cs profile for the soil at this site ($r^2 = 0.97$). The model is:

$$\log_{10} C_i = 0.933 - 0.034 D_i \tag{1}$$

where C is the mass specific ^{137}Cs concentration (Bq kg^{-1}), D is the soil depth (cm) and i is the sample depth increment. The values of 0.034 and 0.933 represent the terms S and E in Eq. (2) below but are not appropriate for the Plateau region. The ^{137}Cs inventory predicted by the model for this site (2066 ± 125 Bq m^{-2}) is the best approximation of the reference ^{137}Cs inventory for an 'undisturbed' site in the study area (Chappell, 1995). It is acknowledged that a more precise estimate of the fallout inventory would require many samples (Sutherland, 1994), but these are unavailable in the present case.

To calculate the net soil flux a relation between the movement of ^{137}Cs and the redistribution of soil must be established (Walling and Quine, 1990). The model developed by Zhang et al. (1990) for rangeland areas was used here to estimate surface lowering at erosional sites, although it cannot be used for depositional sites. It utilises the widely reported exponential depth distribution of ^{137}Cs in rangeland areas to estimate the depth of soil removed from a site from the difference between the ^{137}Cs remaining in the profile and the ^{137}Cs reference level:

$$Y = 100 \ln(1 - X_1)/-SPE \tag{2}$$

$$X_1 = (R - A)/R$$

where Y is mean annual soil loss (t ha^{-1} yr^{-1}), S is the depth distribution shape coefficient, P is the number of years since 1963 and X_1 is the reduction ratio of the total ^{137}Cs activity per unit area (A), at each site, relative to the reference inventory (R) in the same units (Bq m^{-2}). A value of 0.144 was used for S to represent the shape coefficient of ^{137}Cs profile on the Plateau soils. Since the thin soil on the Plateau was known to be approximately 20 cm in depth before the soil matrix was dominated by ferricrete cobbles, an additional term (E) with a value of 1.5 was used in the net soil flux model (2) to offset the total depth of soil removed. It was derived from empirical model fitting using existing soil ^{137}Cs profiles in this region (Chappell, 1995).

An additional model is needed to define the relation between ^{137}Cs and net soil gain. It is reasonable to assume that sites of accumulation are the result of deposition either from surface wash or the wind, and that both are more likely to occur beneath vegetation. Surface wash deposits are likely to have a uniform ^{137}Cs profile with depth. By assuming further that the ^{137}Cs concentration of the mobile aeolian material accumulated beneath vegetation is approximately constant, its ^{137}Cs depth-distribution should also be uniform. Thus, the modified proportional model suitable for establishing the mean annual net soil gain for sites along the transect which have ^{137}Cs activity greater than the reference level is:

$$Y = 10(DBX_2F)/T \tag{3}$$

$$X_2 = (A - R)/A$$

where Y is the mean annual net soil gain (t ha^{-1} y^{-1}), D is the sample depth (m), B, the bulk density of soil (kg m^{-3}), X_2 (the reduction ratio of the total ^{137}Cs activity per unit area at each site as defined above), F is the adjustment which accounts for the preferential accumulation of ^{137}Cs (0.1) and T is the time elapsed since 1963 (years) to enable comparison with the equation for net soil erosion (Eq. (2)). No adjustment has been made for the preferential accumulation of dust in the samples.

3. Results and discussion

The particle size distributions of samples along the transect selected from within and between the vegetation bands (Fig. 2) show large amounts (60–80%) of silt and small amounts of sand and clay. The silt mode dominates all samples. At sites protected from wind erosion by a vegetated canopy, this is probably due to the accumulation of aeolian dust (McTainsh and Walker, 1982). At unprotected sites between the vegetation bands the accumulation of aeolian material is unlikely. Here the dominance of silt suggests that the silt-rich aeolian accumulations in the vegetation bands have been redistributed to the interband by surface wash. This may occur when intense rainfall reaches a soil where vegetation has died out, for example in the degraded zone of the band (Thiery et al., 1995). It is hypothesised that a decrease in the vigour of plants in the lower part of a band is caused by a reduction in moisture and nutrients which results from the capture of moisture and nutrients by plants colonising the upper part of the band (Thiery et al., 1995). This process is reflected in a temporal succession of different soil crusts (Valentin and Bresson, 1992). The decline in vegetation cover on the lower edge of the band exposes soil to intensive rainfall causing the development of structural crusts which maximise runoff and which remain unaltered because of reduced termite activity. The acceleration of runoff in this zone increases erosion, removes the structural crusts and exposes the gravely layer. This in turn produces gravel crusts which generate even more intense runoff, but protect at the same time the soil from further degradation. The accumulation of wash deposits in the sedimentation zone reduces the slope gradient allowing the formation of sedimentation crusts.

The proportion of the clay and silt fraction (Fig. 2) in the soils of the degraded zone is very similar to that found in those of the central zone. The proportion of clay and silt in soils decreases across the degraded and runoff zones whilst that of sand increases.

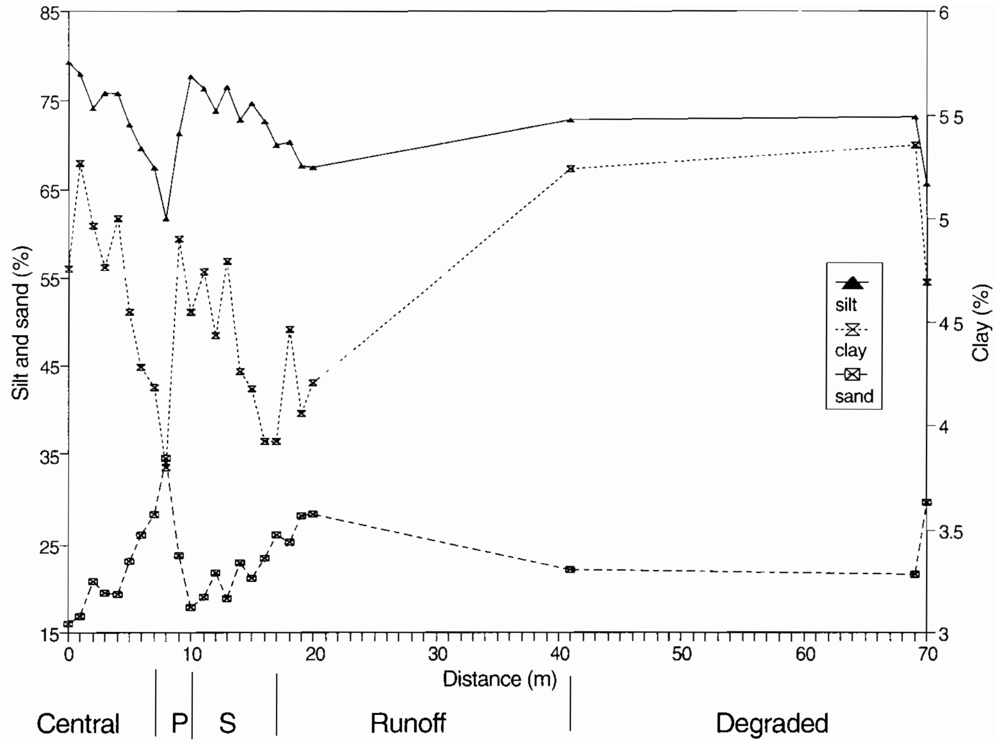

Fig. 2. Proportion of sand (> 1128 μm), silt (> 60 μm) and clay (< 2 μm) fractions in the soil along the soil sampling transect.

Structural and gravel crusts were identified in these zones (Table 1). There is a remarkable similarity in the distributions of silt and ^{137}Cs along the sample transect (Fig. 3): both generally decrease downslope from the degraded zone across the runoff zone and both increase in the sedimentation zone. There is also a strong relationship between crust types and brousse tigrée zones (Table 1). In general, the distribution of the mobile silt and clay fractions, of ^{137}Cs and of soil crusts suggest that soil is eroded in the degraded zone, transported across the runoff zone and deposited in the sedimentation zone.

The distribution of ^{137}Cs-derived net soil flux along the transect (Fig. 4) varies between -63 t ha^{-1} yr^{-1} and $+14$ t ha^{-1} yr^{-1}. The average net soil flux for each of these zones (Table 1) reveal a general pattern of decreasing net soil flux and show a strong relationship with crust type. The equivalent total soil loss depth is shown (Table 1). Sites in the degraded and runoff zones have the largest net soil loss amounting to an average total soil depth loss of 14.7 cm. In general, the levels of ^{137}Cs in the soils of the central and pioneer zones are slightly lower than the reference level (2066 ± 125 Bq m^{-2}) and hence these soils must have suffered net soil loss. Single net soil flux measurements from other interbands in the region (Chappell, 1995) have shown similar values for net soil flux (between -90 t ha^{-1} yr^{-1} and $+5$ t ha^{-1} yr^{-1}).

The only site of net soil gain in the present transect exhibits a rate considerably greater than that of the average annual dust accumulation (4 t ha^{-1} yr^{-1}), measured using the ^{137}Cs technique (Chappell, 1995). The large difference between these results suggests that the soil gain at this site is probably due not only to the accumulation of material redistributed by surface wash but also to the accumulation of dust. Adjacent to this site of net soil gain there is a micromound (Fig. 4) which coincides with the localised net soil loss probably as a result of surface wash from this point. This process probably accounts for the structural crusts in the pioneer zone (Table 1), the increased proportion of silt (Fig. 2), the decreased proportion of sand and the large net soil gain (Fig. 4). It is reasonable to suppose that similar processes are operating to remove soil

Table 1
Spatial extent along the sampling transect of brousse tigrée zones, soil crust classes and the average net soil flux per zone

Brousse tigrée zones	Central	Pioneer	Sedimentation	Runoff	Degraded	Central
Sample labels	A–G	H–J	K–Q	R–U	V–X	
Distance (m)	0–7	7–10	10–17	17–41	41–72	72–73
Soil crust location (m)						
Sieving, erosion and gravel		8.3–9.4	11–17	17–41	41–67	
Sedimentation		9	10–17			
Net soil flux (t ha^{-1} yr^{-1})	-5.10 ± 0.4	-16.67 ± 3.58	-7.61 ± 1.10	-43.17 ± 16.60	-25.74 ± 3.0	
Total soil depth (cm)	-1.6	-5.3	-2.4	-14.7	-8.8	

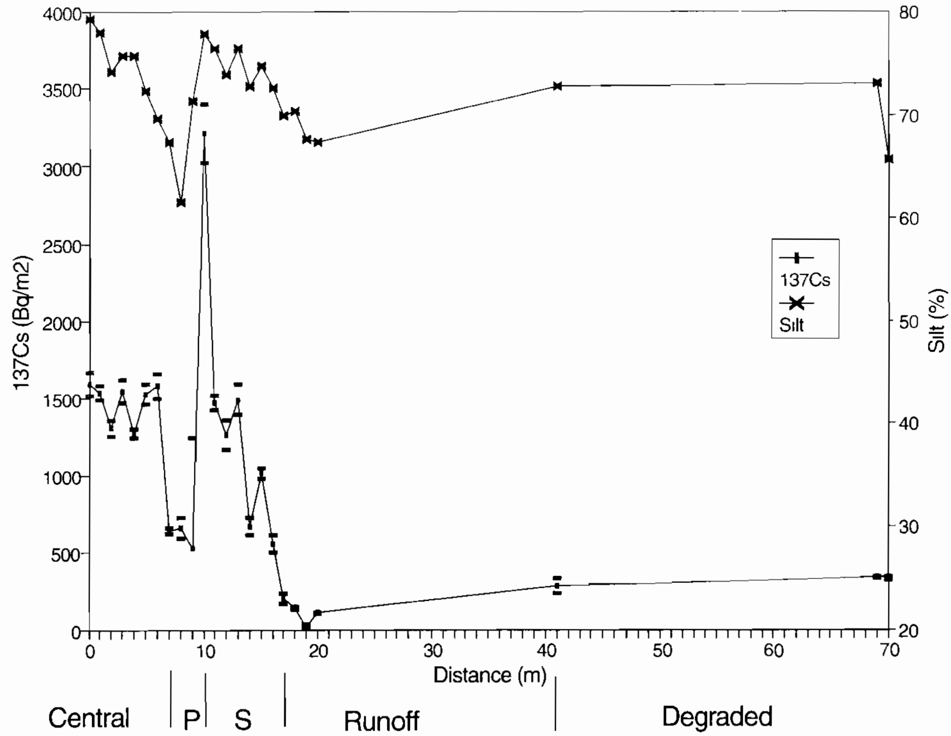

Fig. 3. Spatial distribution of ^{137}Cs (Bq m^{-2}) and silt content along the soil sampling transect.

from beneath the vegetated canopy and that they result in the general net soil loss in the central zone of the vegetated band.

A more plausible explanation for net soil loss in this central zone might be thought to be that when intense rainfall causes flooding in the upslope bare lane and the soil in the band is already nearly saturated, flood-water passes into and through the vegetated band (Thiery et al., 1995; p. 501). However, in the bands surrounding the present transect moisture levels were found (with neutron probes) to be large (Galle et al., this issue) and porosity is also thought to be large at these sites because of termite activity (Thiery et al., 1995). This suggests that the flood-water processes invoked to explain the net soil loss in the vegetated band sampled in this study do not take place in other vegetated bands. The difference between this transect and others may be the relatively steep gradient in the central and degraded zones downslope of the micromound (Fig. 4) which probably accelerates drainage and surface wash causing localised net soil loss.

Upslope of the micromound along the present sampling transect there has, in general, been net soil loss for the last three decades (Fig. 4). Nonetheless, the presence of sedimentation crusts (Table 1), the increasing silt content (Fig. 2) and the decreasing rate of soil loss (Fig. 4) in the sedimentation zone, all suggest that recent deposition has occurred on a previously eroded surface. This accumulation has occurred at least in the last 19 years, on the evidence of the dendrochronology date for a tree (*G. senegalensis*)

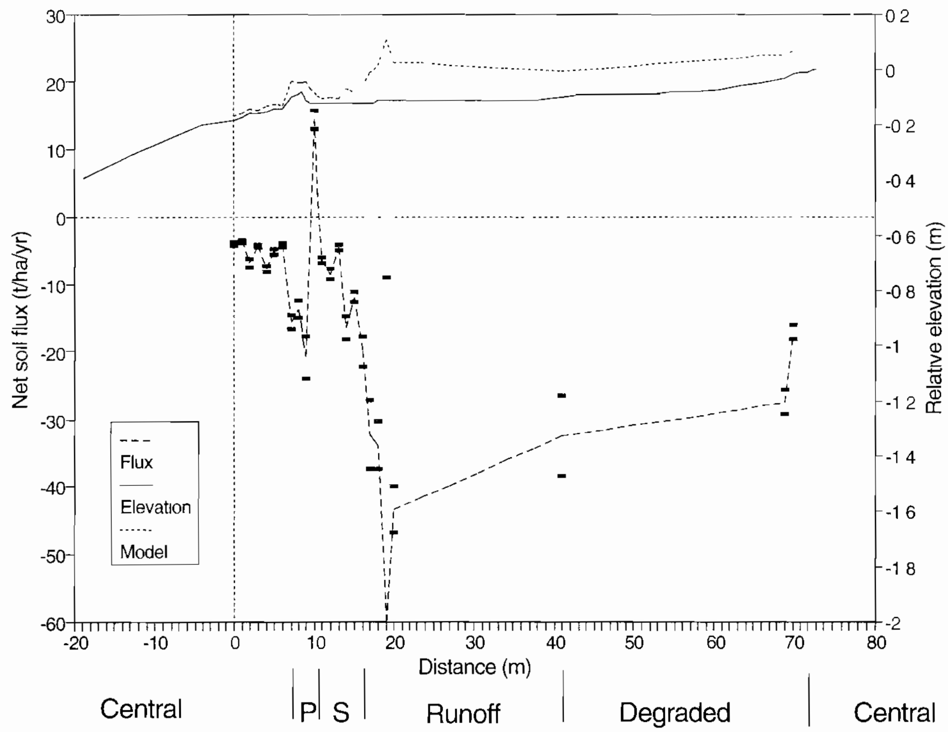

Fig. 4. Spatial distribution of net soil flux, measured relative elevation and modelled original relative elevation along the sampling transect.

located in the pioneer zone, adjacent to the site of net soil gain. The micromound probably creates a barrier for low intensity surface wash events and promotes sediment deposition, seedling emergence and, since deposition tends to decrease the slope gradient (Fig. 4), the upslope migration of the band. Thus, the accumulation rate in the sedimentation zone is a function of net soil flux and distance and it is tenable to propose that the distance of upslope migration of the vegetation band is the same as the distance between the centre of the micromound and the upslope edge of the sedimentation zone. This edge appears to be between the sedimentation and runoff crusts located respectively at 7 m and 8 m from the micromound centre. Thus, a first approximation to the upslope migration rate, provided by dividing the extent of the sedimentation zone by the approximate minimum duration of deposition (19 years, as indicated by the tree date), is 0.37 m yr^{-1} and 0.42 m yr^{-1}.

Assuming that the upslope migration rate is constant, a more rigorous estimate of the distance of upslope migration can be predicted from a measurement of total soil loss at the edge of the sedimentation zone using the regression equation:

$$M = -0.0618F + 2.1902 \tag{4}$$

where M is the upslope distance from the centre of the micromound; and F is total soil loss (kg m^{-2}). The regression procedure minimises the least squares variation ($r^2 = 0.83$)

of the distance from the centre of the micromound and total soil flux for samples between the site of maximum net soil gain and minimum net soil loss (Fig. 5). The inclusion of an intercept term significantly improves the least squares fit. Although the site of net soil gain is included in the sedimentation zone, it was not included in the calculation of the regression equation because it was thought that the soil had accumulated from aeolian deposition and soil erosion from the micromound. Samples associated with runoff crusts in the runoff zone were included in the analysis because they improved the fit of the regression line. The total soil losses for sites bordering the sedimentation and runoff zones (-63.82 kg m^{-2} and -103.03 kg m^{-2}, respectively) were derived by multiplying the net soil loss at these locations (-1.99 kg m^{-2} yr^{-1} and -3.21 kg m^{-2} yr^{-1}, respectively) by 32, the total number of years. These total soil losses were substituted into Eq. (4) and provided a distance from the micromound of 6.1 m and 8.6 m, respectively, which resulted in a mean annual upslope migration rate of 0.19 m yr^{-1} and 0.27 m yr^{-1} for the last 32 years. This migration rate is consistent with detailed observations of digitised aerial photographs from 1950, 1975 and 1992 (Mougenot et al., in preparation) which produced a mean annual migration rate of between 0.2 m and 0.8 m from 1950 to 1975, and between 0.12 m and 0.48 m from 1950 to 1992.

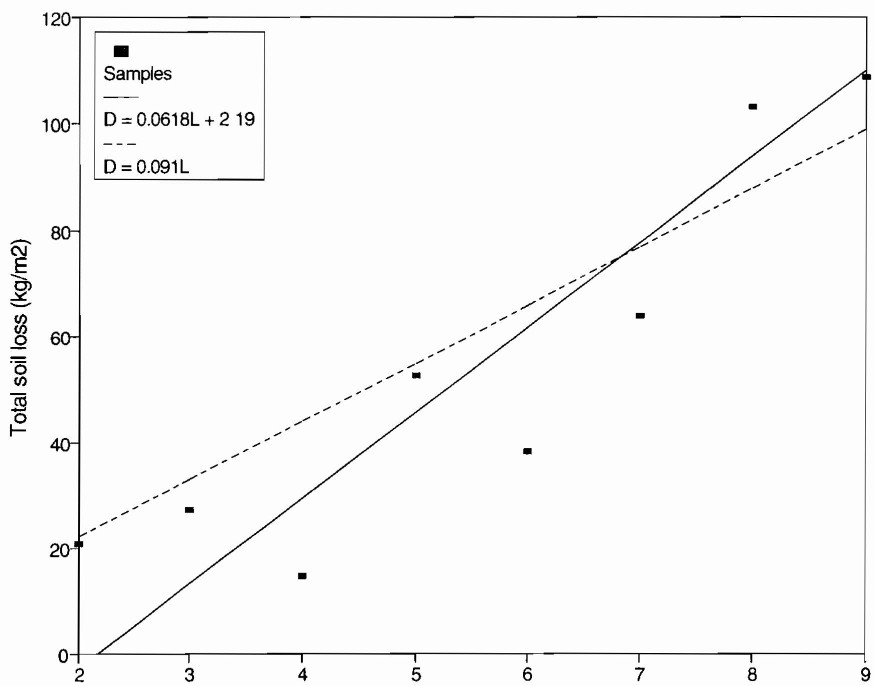

Fig. 5. Scatter plot of net soil loss and distance from micromound with fitted least squares linear regression lines.

4. Summary and conclusions

The ^{137}Cs technique for measuring net soil flux identified the vegetation band and the interband as zones of net soil loss. However, the soil texture, crust type and the ^{137}Cs content of samples obtained along the transect show that there is a decrease in net soil loss, resulting from recent accumulation, in the sedimentation zone of the downslope vegetation band. These apparently contradictory results are probably due to the particular band of this sample having a relatively steep topographic gradient that produces good drainage, which in turn results in localised surface wash and erosion processes beneath the vegetation. The accumulation on the upslope side of the vegetation band is probably caused by the presence of a micromound, which has reduced surface wash and enhanced deposition. There is corroboration of such accumulation in the evidence of the sedimentation crusts and in the model predictions for the upslope migration of the vegetation band (Thiery et al., 1995). The rate of accumulation in the sedimentation zone was considered to be representative of the upslope migration rate which was calculated to be approximately 0.19–0.27 m yr^{-1}.

These results show that the average annual migration rate of the banded vegetation can be calculated from accurate measurement of net soil flux for the last 32 years using the ^{137}Cs technique. The spatial variability along the transect (across the band) was anticipated but the variation along the vegetation band was not. It is necessary to ensure that a single transect is representative of the pattern of soil redistribution. This should be done either by detailed topographic sampling prior to soil sampling or by improved soil sampling which encompasses the spatial variation across and along the vegetation bands. Both approaches must account for the observed occurrence of the bay and headland pattern in the pioneer zone of the vegetation bands as this may be caused by differences in micro-topography and lateral flow between the vegetation bands.

In order to develop the ^{137}Cs technique for measuring soil redistribution in this environment many samples would be required which would be very time-consuming. A viable alternative might be to develop the relationship established here between different types of crust and their ^{137}Cs content to produce a calibration curve for rapid calculation of net soil flux from different crust types.

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