The use of remote sensing in quantifying rates of soil erosion

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A remote sensing technique is applied in the quantification of the aereal involvement and rates of spread of sodic sites in the upper Ripape River drainage basin of the Kruger National Park. The results show changing areas of sodic site erosion over a period of 41 years. Possible cause and effect relationships are not discussed but the magnitude of soil loss suggests that the erosion has progressed at a rate which is in excess of the rate of natural denudation, under the prevailing climatic regime.

Keywords: remote sensing, sodic sites, erosion.

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Introduction

The role played by the soil resource in maintaining the integrity of rangeland systems is widely recognised. Botkin (1981) views the condition of this resource as a sensitive indicator of the system's wellbeing and Macdonald (1989) states that for all practical purposes the soil should be regarded as a non-renewable resource. Roberts (1985) points out that the dynamics of any vegetation system can only be sustained while the edaphic potential is maintained. This author claims that the importance of soil overrides the importance of changes in the biotic component in maintaining range productivity. Productivity and sustainability have been cited as the vital issues in savanna management (Walker 1985). Cooke & Doornkamp (1990) regard, as central to environmental management, the need to develop appropriate monitoring techniques that take the soil into account.

Notwithstanding the acknowledged importance of the soil resource and its role as a major determinant in savanna ecosystems, those processes which impact unfavourably on it have not been widely studied. That processes which have the potential for degrading the system and adversely affecting its productivity are of concern is witnessed by the ongoing research which focuses on the management of the biotic component. For similar reasons soil and soil nutrient losses, due to erosion, deserve a prominent place in the planning and execution of management strategies, particularly in view of the geological time scales involved in soil formation.

Soil erosion under rangeland conditions is seldom visually spectacular and its effects on productivity manifest only slowly. Under these conditions this form of land degradation is seldom viewed with concern and is often accepted as a natural process of interest only in geomorphic terms. In order to confirm or refute this widely held belief it is necessary to distinguish between 'natural' or 'geological' erosion and accelerated forms of soil loss. To address this question a method was developed to determine the rate of soil loss from eroded sodic sites in the upper Ripape River catchment area.

The sites selected to develop this method formed part of a larger area in which a detailed study of the processes surrounding sodic site development were investigated (Chappell 1992).

This project included a detailed analysis of textural, structural, permiability and chemical attributes of the soils. In addition the species composition and distribution of the vegetation communities were examined in relation to the catenary soil sequences. The intimate knowledge of the surface features that was gained during the larger study was invaluable in the interpretation of the aerial photographs. This is regarded as an essential prerequisite where photographs are taken over an extended time period and are therefore processed at different times by different individuals.

Natural versus *accelerated erosion*

On a time scale measured in decades the active, year to year, forces of erosion are, in general, not of sufficient magnitude to disrupt the approximate balance between the rate of weathering and soil formation, on the one hand, and the rate of natural denudation on the other (Selby 1990). The assumption is made that geologically normal rates of soil erosion operate within ecosystems that are in a state of dynamic equilibrium. Beckedahl *et al*. (1988) conclude that accelerated erosion is a manifestation of ecological disequilibrium.

Natural and accelerated erosion have in common detachment, entrainment, and transport of the products of weathering. The major difference resides in their respective rates and their characterisation on this basis is fundamental if realistic target goals for conservation practices are to be set.

Sediment yield data and erosion plot experiments have been used to quantify rates of natural erosion under a wide variety of environmental and experimental conditions, for example Schumm (1977) and De Ploey & Gabriels (1980). Weathering boundary maps (Weinert 1965), and isoerodent maps (Smithen 1980) have been compiled for the southern African region but on a local scale the rate of natural erosion remains largely a matter of opinion. In the absence of local data students of this topic must rely on the generally accepted equilibrium concept previously referred to.

Erosivity and erodibility

Models of erosion, for example the Universal Soil Loss Equation (Wischmeier 1976) have been based on the fundamental distinction between erosivity (the potential of a process to cause erosion) and erodibility (the vulnerability of a soil to erosion). Using these, or similar models, it has been possible to identify, in any given region, the major factors responsible for erosion (Stocking 1972; Stocking & Elwell 1973). The application of these data, in erosion hazard assessments, are discussed by Beckedahl *et al*. (1988). These authors regard erosion hazard assessments as a necessary preliminary to any land management decision.

In the Kruger National Park soils research has focused on classifying and mapping soils on the basis of their physical and chemical properties (Joubert 1982). These data have been used, together with plant community distribution data, to identify landscape types as an aid to range management (Gertenbach 1983).

The relationship between soils and the underlying geology has received attention and, where they occur, catenal soil associations have been described (Venter 1986). Although the soils have not been formerly assessed in terms of their erosion potential it is accepted that those derived from granite and related substrates, owing to their physical and chemical characteristics, are particularly susceptible in this regard.

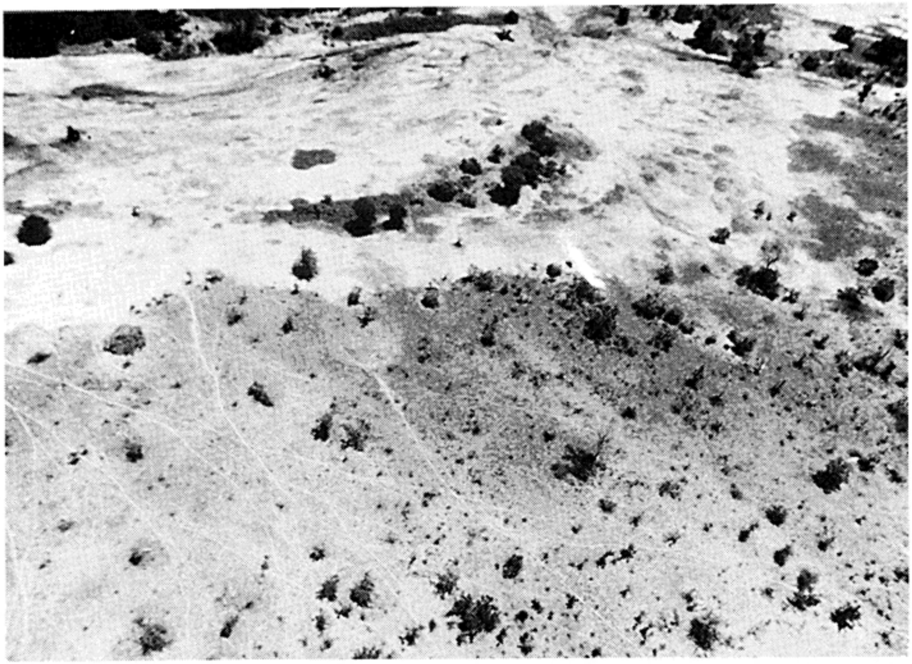

Fig. 1. The footslope location and general features of a sodic site (oblique aerial photo).

Sodic sites

One form of erosion which granitic soils exhibit is to be witnessed in the formation and widespread occurrence of sodic sites. These are commonly referred to as 'brak kolle'. Sodic sites are usually located in the footslope segment of the hillslope, they tend to parallel the drainage channel, and may extend for variable distances onto the base of the midslope. These areas vary in extent from a few square metres to several hectares (Fig. 1).

A study of sodic sites has revealed the unique nature of the processes involved and has demonstrated the role which subsurface water movement plays in their genesis and spread — a process that was formerly thought to be due to surface runoff originating from regions higher on the hillslope (Chappell 1992).

A feature of fully developed sodic sites is that they represent the loss, by erosion, of the entire thickness of the A horizon soils. The exposed surface is typically the clay of the B horizon covered by a veneer of angular white quartz sand. These angular clasts represent the skeletal remnants of the A horizon and are originally derived from the granitic rock substrate. Sodic sites frequently exhibit, along their upslope margins, a distinct ledge or scarp which clearly delineates the eroded area below and the the uneroded, intact, soils on the slope above. The vertical height of the scarp reflects the depth to which the erosion process has progressed (Fig. 2).

The bottomlands in these granitic landscapes have been described as open tree savannas supporting – if not overgrazed – a dense grass cover (Gertenbach 1983). The game tracks which cross and recross these areas, the abundant deposits of dung and in many instances the formation of large middens, indicate that these areas are favoured by many species of game. A number of reasons have been offered to explain why these areas tend to be favoured. Bailey (1990) has shown that the

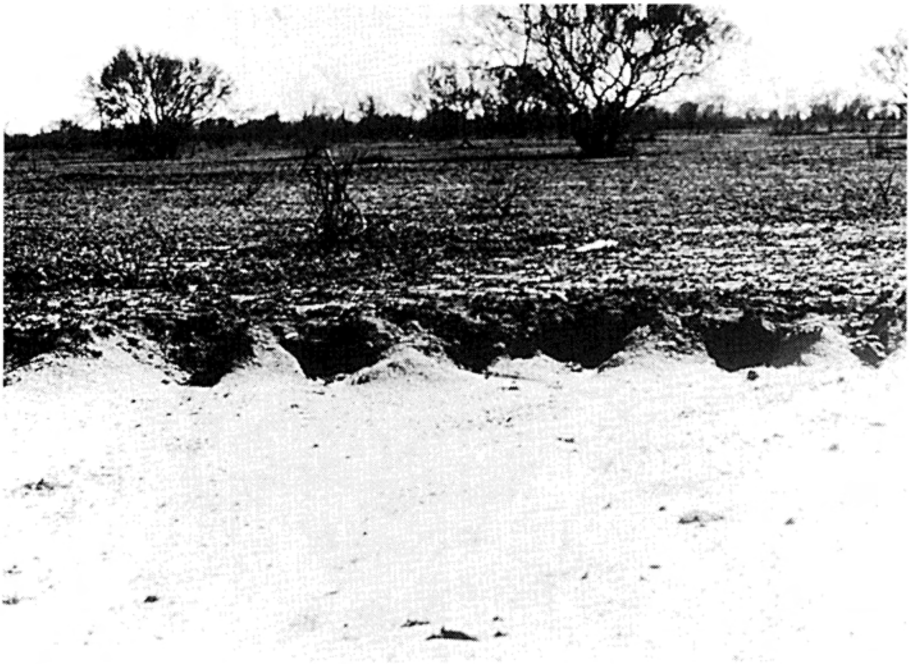

Fig. 2. The erosion scarp at the upslope boundary of a sodic site showing piping erosion outfalls.

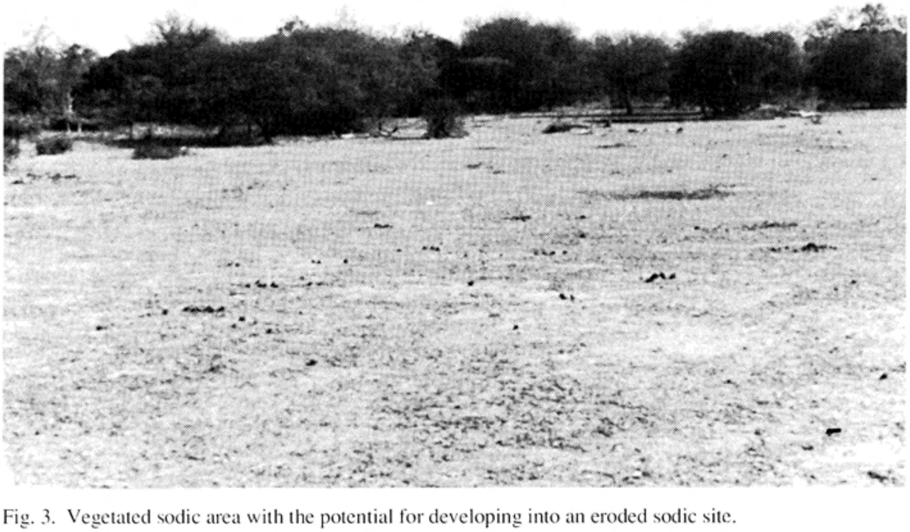

Fig. 3. Vegetated sodic area with the potential for developing into an eroded sodic site.

grasses growing on these sodium-rich soils accumulate high levels of this element in their leaves. Surface depressions on the impermeable sodium-dispersed clays accumulate water during the wet season and are the focus for the formation of mud-wallows which attract many animals. Weir (1971) records that certain game animals display a distinct preference for areas in which the soils and surface water contain appreciable concentrations of salts, particularly sodium, and that these soils are frequently licked and even ingested by several species of ruminants. The physiological role played by sodium in maintaining the electrolyte balance in ungulates with ruminant-like digestions is discussed by Blair-West *et al.* (1963), and this appears to be particularly important in arid and semi-arid climates.

Apart from being a source of minerals the openness of these areas and the generally short grass cover may play a role in predator avoidance and contribute to their attractiveness, particularly to short grass grazers (Fig. 3).

In situations where the protective grass cover has been heavily overgrazed, or destroyed by excessive trampling, the aggregate structure of the A horizon soils – inherently low in organic matter and generally coarse textured – is compromised to the extent that they erode rapidly and the underlying B horizon clays become exposed at the surface. Any management practice that promotes high grazer concentrations on these sites has the potential for accelerating the destruction of the grass cover and promoting sodic site formation.

Following the loss of topsoil the exposed clays of the B horizon soils do not constitute a suitable seedbed for the re-establishment of grass cover and these areas remain as bare open patches in the landscape (Scholes 1986). Viewed in terms of ecosystem dynamics sodic sites are an example of a system having crossed the threshold from one equilibrium state to another of lower productivity. There is a widely held perception that sodic sites represent an example of natural erosion, are an integral part of the ecosystem, and should be recognised as such. As part of a broader study of the ecology of sodic sites in general it was necessary to quantify the rate of soil loss from these areas.

Methods

Remote sensing of eroded sodic sites

The study area is located in the upper Ripape River catchment, close to the western boundary fence of the Kruger National Park. (Fig. 4).

The white quartz clasts that cover established sodic sites constitute a high albedo surface easily recognised visually in the field by its bright appearance (Figs. 1 & 2) and on Remote Sensing images by a very high overall albedo in all wavelength ranges (Fig. 5). Other surfaces in the surrounding area have some vegetative component which has a markedly lower overall albedo in the visible wavelengths. Areas of bare sandy soil that are not eroded may have albedo values approaching that of the eroded areas being dominantly composed of quartz clasts albeit of finer grain size. Mature erosion areas that have had the quartz clasts stripped to expose the underlying clay, or have been re-colonised by ephemeral grass or blue-green algae, lose the bright appearance in the visible wavelengths.

The images used to measure erosion extent were panchromatic aerial photographs. This choice was due to three factors:

- photographs ranging from 1:20 000 to 1:50 000 scale provide the requisite detail necessary for monitoring of the present study area;
- multi-temporal aerial photographs are available over a period of 50 years, encompassing over half the life span of the Kruger National Park;
- the areas of erosion are high albedo areas comprising the brightest areas on the photographs and are therefore easily discriminated from other surface types on panchromatic photographs.

Panchromatic vertical aerial photographs from four periods have been used to monitor soil erosion in the Ripape River study site. The photographic sorties were flown in the winters of 1944, 1965, 1974 and 1985. A large difference between the appearance of the area in 1944 and more recent times is clearly visible (air photo split 1944/1974). (Fig. 5).

Scale and albedo problems

The photographs from each period differ in scale, orientation, and image density/contrast making it difficult to carry out visual estimations and comparisons

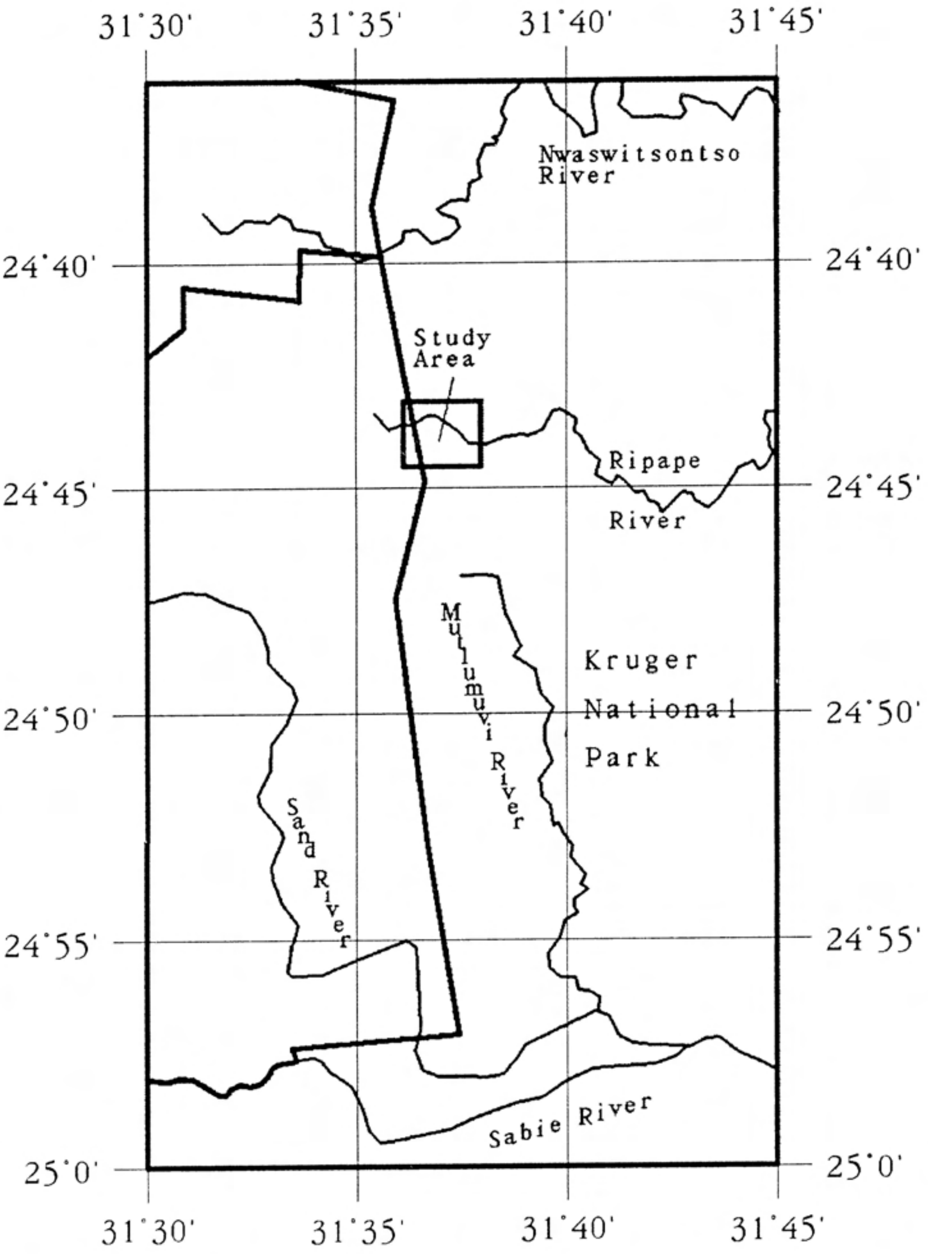

Fig. 4. Location of study area.

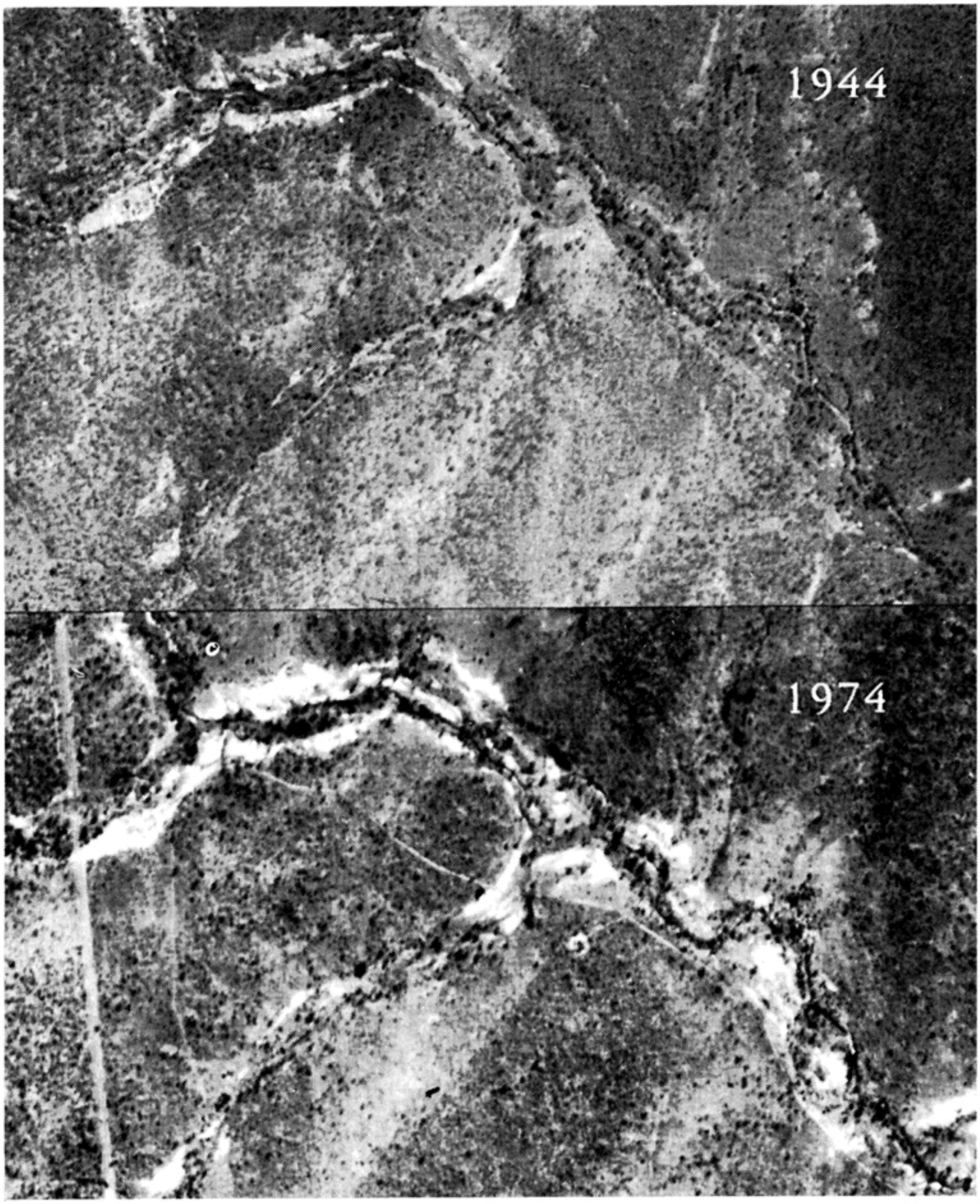

Fig. 5. Comparison of vertical aerial photographs of the study area from 1944 and 1974 showing significant development of eroded sodic sites between these years.

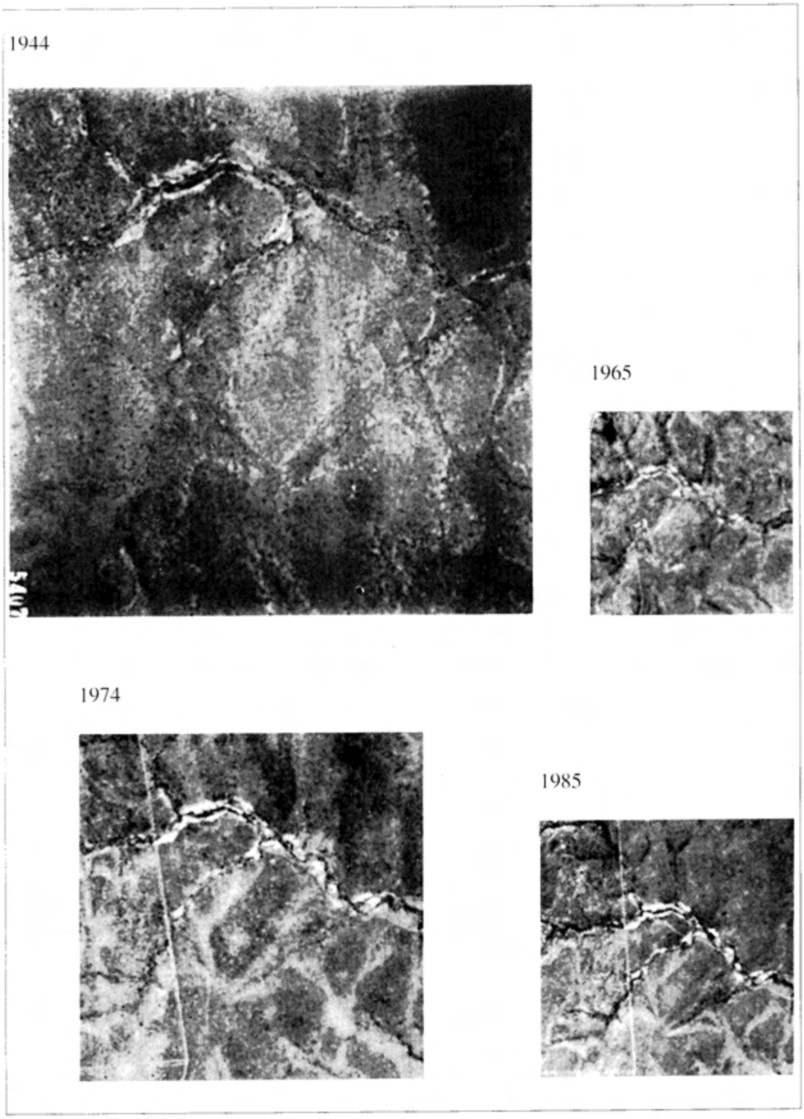

Fig. 6. Comparison of relative scales of vertical aerial photographs from 1944 to 1985 before digital georeferencing and re-sampling.

of the amount of erosion present at each time (Fig. 6 – photographs at original relative scales). These problems were overcome using digital processing techniques.

Digital Image Processing

Image processing was carried out on an IBM compatible 486 33Mhz PC using the MicroImages MIPS (Map and Image Processing System) software. This software is particularly applicable to this application with sophisticated routines for registration of remote sensing data to map projections and measurement of surface categories. Digitisation of the aerial photographic prints was by means of a Howtek Scanmaster 3 digitising scanner directly driven from MIPS.

One photograph from each set was chosen for digitisation. The chosen image contained the study area as close to nadir as possible. The study area was then digitised from each photograph using a spatial resolution of 150 dpi (dots per inch) and an 8 bit grey level range (0–255). The limit of the study area digitised from each were chosen from the limits of the largest scale photo. This was the 1944 photo at approximately 1:20 000 scale.

The 1944 image was also used as the bench mark for registration and resampling of the photos to the same map projection and pixel size to facilitate measurement and comparison of eroded areas from each period. Ground control points (GCPs) were chosen from this photograph and 1:50 000 scale topographic maps. The 1944 digitised photo was then resampled to a Universal Transverse Mercator projection using the Clark 1880 ellipsoid. Resampling was by the nearest neighbour method with an output pixel ground dimension of 1,3 metres.

Ground control points were chosen from the georeferenced 1944 photograph and the photographs from 1965, 1974 and 1985. These were subsequently resampled to a UTM projection at 1,3 m pixel. The resultant set of four georeferenced photographs now represented the same area at the same scale so that direct measurements and comparisons of areas of ground surface type could be made.

Measurement of erosion areas

The overall albedo of three surface types was established by interactive image analysis for each of the four photos. The ranges in intensity for trees, grass and bare ground are shown in Table 1. The areas devoid of vegetation are clearly the brightest surface types on the digital images and a threshold value, equal to the lowest value for the 'bare ground' category, was chosen for each image. A binary image was then generated with a value of zero for any pixel below the threshold value and a value of one for any pixel equal to or above the threshold. Vector polygons were then drawn around the erosion areas on the binary image using an 'automatic boundary' feature of MIPS. The resulting vector object could then be plotted and interrogated to discover the total area covered by the erosion sites.

Table 1
Digital number (DN) ranges for cover types on digitised aerial photographs

Year	Trees	Grass	Eroded
1944	21–55	67–119	121–157
1965	50–81	86–136	145–178
1974	15–54	62–132	138–178
1985	14–53	66–131	135–173

Table 2
Mean Erosion Scarp Height and Dry Bulk Density of A-horizon soils

	Sample Size	Mean	SD	Variance
Scarp Height cm	200	29.0	5.92	35.06
Dry Bulk Density kg/m^3	20	1.67	0.32	0.10

Soil loss estimation

Figure 7 shows an increase in area of sodic site involvement of approximately nine hectares between 1944 and 1974.

To obtain an estimate of the quantity of soil lost to the erosion process an estimate of the average scarp height was obtained from 200 theodolite readings taken over a 500 m distance. The mean dry bulk density of the A horizon soils was determined from 20 undisturbed soil samples, of known volume, taken from the base of the midslopes of four study catenas, oven-dried and weighed. Results are given in Table 2.

Results

Remote sensing results

Vector polygon and total area measured for each of the four photographs are shown in Fig. 7.

The amount of bare ground in 1944 is 0,64 hectares. Most of this is along the Ripape drainage system and associated with sodic sites. There is a group of areas along the top margin of the photo that are not bare ground. These are areas that have brighter intensities along the edge of the photograph and are apparently due to a photographic abberation. The measured area is therefore an overestimation.

The measured amount of bare ground for 1965 is 6,5 hectares. This is dominantly along the Ripape drainage system associated with sodic sites although some small areas also occur along a seep line, which is normally

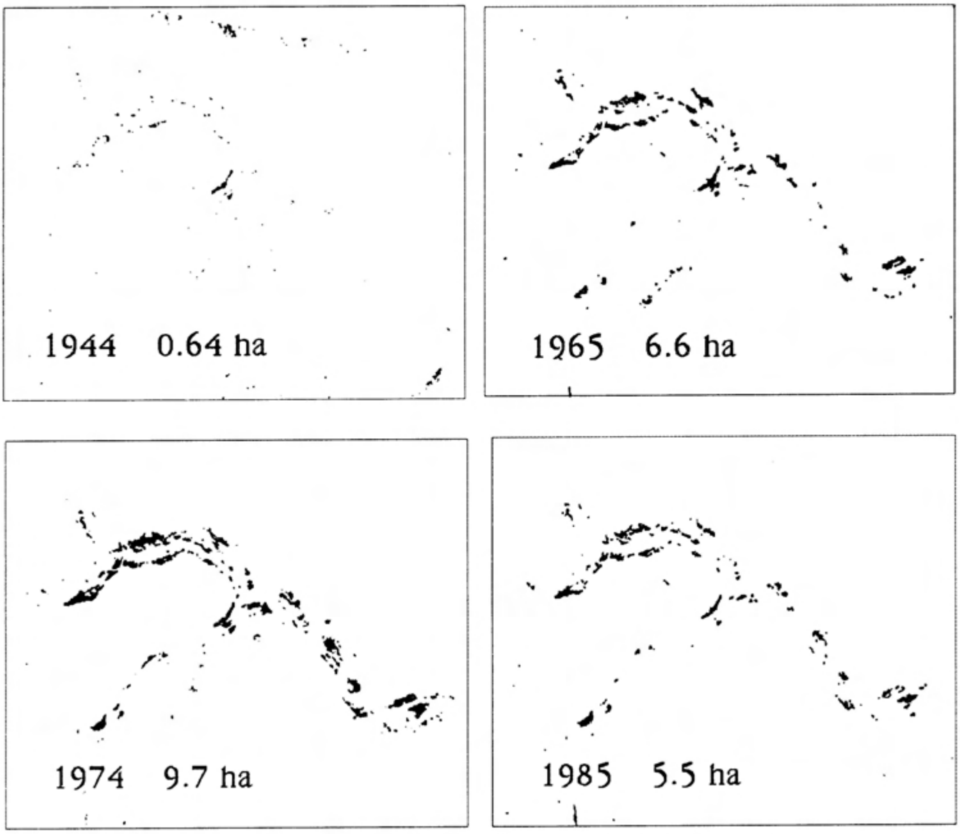

Fig. 7. Vector polygons indicating location and total area of eroded sodic sites in the study area for the years 1944, 1965, 1974 and 1985.

grass-covered, in the south central part of the study area.

The measured amount of bare ground for 1974 is 9,7 hectares. This is dominantly along the Ripape drainage system associated with sodic sites and is the maximum development observed from the four periods.

The measured amount of bare ground for 1985 is 5,5 hectares. Erosion area locations are practically identical to the 1974 imagery but the measured areas are smaller (Fig. 8).

Soil loss estimation

The area recorded as bare ground and equated with sodic site involvement reached a maximum in 1974. The annual increase in bare ground from 1944 to 1974 was 0,3 hectares.

The mean height of the upslope erosion scarp (0,29 m) is used as an indication of the depth of soil lost as a result of the erosion process. The calculated volume of this soil is 870 m^3. At a dry bulk density of 1,67 the mass of this volume of soil is 1 459 kg, which represents the mass lost for each additional 0,3 ha of erosion. On a per hectare basis the figure is 4 843 kg ha^{-1} yr^{-1}. To facilitate comparison

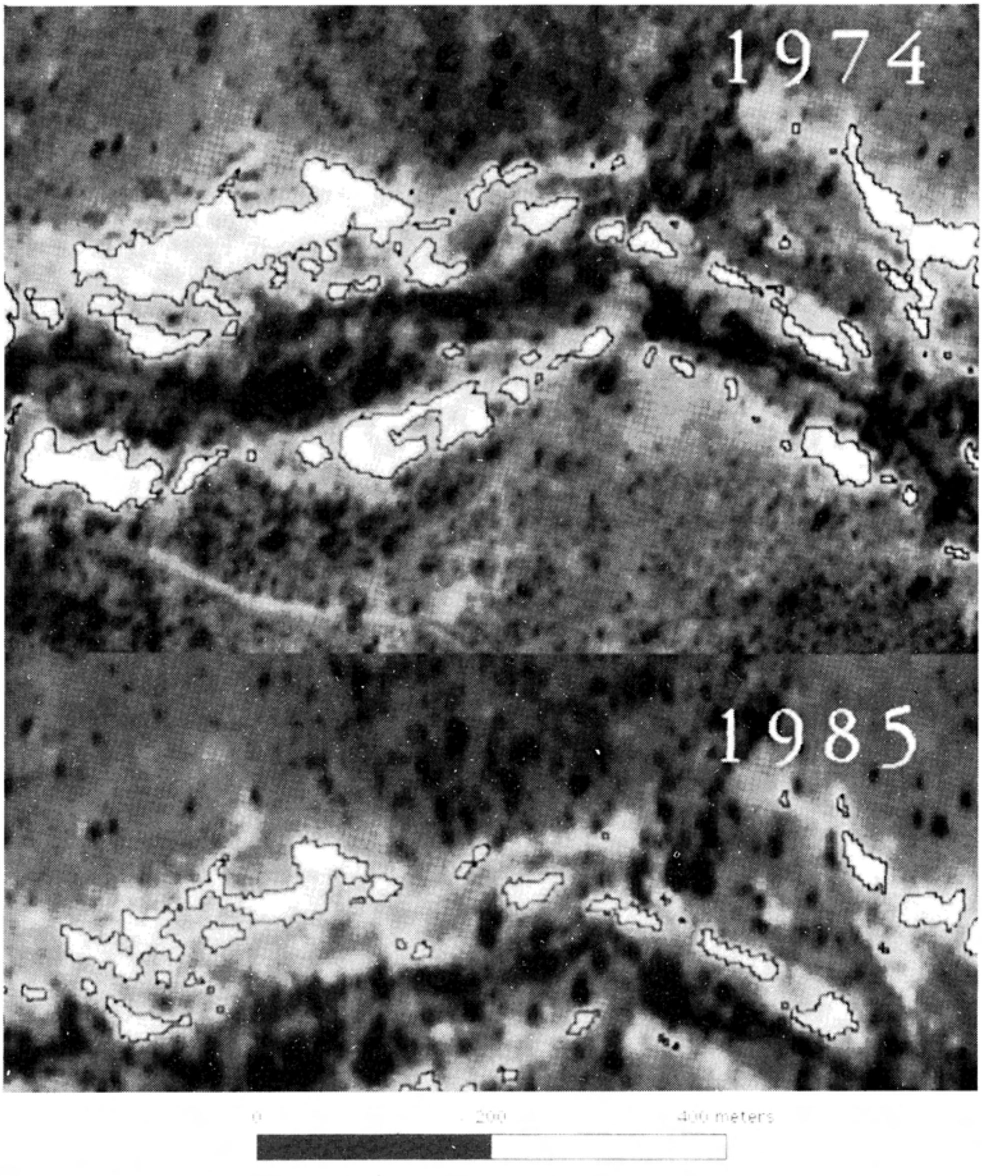

Fig. 8. Detail of aerial photographs covering part of the study area illustrating the decrease in high albedo surface material from 1974 to 1985.

with data reported in the literature, this figure, when converted to tonnes/ha and tons/acre gives, in rounded terms, 5 tonnes/ha and 12 tons/acre respectively.

Discussion and Conclusions

In view of the statement that accelerated erosion is a manifestation of ecological disequilibrium (Beckedahl *et al.* 1988) it is of concern, from a conservation perspective, to determine whether sodic site erosion can be categorised as natural or an accelerated form of soil erosion.

Attempts to quantify rates of soil formation based on rates of chemical and mechanical disintegration of various rock types have been conducted under laboratory and field conditions. Selby (1990) quotes figures for rates of bedrock weathering that approach 0,02 mm/yr and Jenny (1942) reports that weathering rates of 0,05 to 0,1 mm/yr have been recorded for exposed rock surfaces.

Evidence from reliable gauged catchments have been used to predict aggregate denudation rates on a global scale. Saunders & Young (1983) have collated the data from several of these studies and show that for steep relief the median value is 0,05 mm/yr (range from 0,1 to 1,0). For normal relief the median value is 0,045 mm/yr (range from 0,02 to 0,08). The rate of surface lowering in the sodic sites of the Ripape River catchment were found to be 0,96 mm/yr.

Smith & Stamey (1965) have suggested guidelines for soil erosion rates, in terms of what farmers are likely to achieve in cultivated lands, on slow forming erodible soils. They indicate that for acceptable soil conservation practice the upper limit to soil loss is of the order of 2 000 kg ha^{-1} yr^{-1}.

Morgan (1980) considers this to be a realistic figure for areal units of drainage basin size. The figure for the Ripape River study sites (4 843 kg ha^{-1} yr^{-1}) is more than twice the suggested guideline rate.

Kirkby (1980) notes that in current soil conservation practice in cultivated farm lands it is normal to plan for accepted rates of between two and 10 tons $acre^{-1}$ yr^{-1}. This author considers these figures to be too high as estimates of natural erosion and states that losses of this magnitude cannot be tolerated in terms of sustainable land use in the medium to long term.

A review of the literature shows that there is a lack of data regarding rates of soil formation and rates of natural denudation for South Africa in general. The recorded rates of erosion of A horizon soils from sodic sites in the study region, when compared with figures from the literature quoted above, suggest that the process can be regarded as a form of accelerated erosion.

Because of the widespread attitude held by many range managers that sodic site formation is a form of 'natural' erosion the approach in this study has been conservative and the areas defined as eroded were limited to those areas where severe soil loss, involving the entire thickness of the A horizon, had occurred. Had areas with lesser degrees of A horizon truncation been included in the assessment the figures would have been considerably higher.

A common feature of many sodic sites is the progressive erosion of the exposed and highly erodible clays of the B horizon soils. This type of erosion frequently leads to the formation of extensive gullies and dongas. The area selected for the purposes of this paper was known, from a knowledge of the ground surface, to exhibit no donga formation. The erosion in this area involved the loss of the A horizon and to a lesser extent some of the surface clays of the upper B horizon. With the exception of minor rill formation at the soil pipe outlets along the erosion scarp, gullies and dongas were absent.

Serious donga erosion was, however, evident in the wider region. This was observed to occur where game tracks had cut into the subsoil clays, creating the hydraulic conditions favouring piping erosion in the non-cohesive saprolite layer. Subsequent collapse of the piping defects initiated gully and donga formation. The processes involved in this advanced form of erosion are discussed by Chappell (1992) and are not dealt with in this paper. Similarly, as cause and effect in relation to sodic site development are not dealt with here, rainfall data and possible range management related data have been omitted.

The apparent reduction in erosion area in the 1985 image is not interpreted as being due to a reformation of A horizon soils at the margins of previously eroded areas. A possible explanation could be that the erosion has gone one stage further and that areas of dark clay are being exposed, thus reducing the high albedo area detected in the photographs. On the other hand, it may be that the early stages of recovery have come about, and that the previously bare areas are being recolonised by cryptogamic plants and pioneer grasses. Both of these types of vegetation encroachment have been observed in the field in 1991/92.

The remote sensing technique described gives a conservative estimate of the extent and rate of progress of sodic site involvement and an indication of the soil loss attributable to this process. It is suggested that the technique can be used to advantage in monitoring a number of surface processes occurring under rangeland conditions. One of the major advantages of the method is its ability to correct for differences of scale and orientation between the multi-temporal photographs and its objective assessment of areas of involvement.

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