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Satellite and field studies of man's impact on the surface in arid regions

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ABSTRACT

In arid regions with sandy soils, both the steppe protected from excessive anthropogenic pressures and the much brighter areas subjected to such pressures show spectral reflectivities (derived from satellite radiometric imagery) increasing with wavelength (from green to the reflective infrared). The reflectivity dip in the red, characteristic of all plants containing chlorophyll, is absent. In an ecosystem of a steppe protected from man's activities, the soil is stable and crusted. Dead plants either remain in situ or litter the surface as debris. The surface spectral reflectivities (derived from satellite imagery) can be represented as a weighted average of the soil reflectivities and the plant-debris reflectivities (which were measured in the field by a hand-held radiometer). In areas affected by man, the surface spectral reflectivities (derived from satellite imagery) virtually coincide with those of crumbled bare soil (as determined by the hand-held radiometer). There is little accumulation of organic material. In such regions, a sharp albedo increase results from anthropogenic impact (from 0.28 in the case of the protected Negev to 0.45 in the case of the adjacent, impacted Sinai). This albedo difference cannot be explained as directly due to the removal of live vegetation, but is due mainly to an accumulation of dead plants on the crusted soil in the protected steppe and the absence of such an accumulation in the impacted regions. Models of the nadir reflectivity as a function of the fractional cover by plants or plant debris (either scattered on the surface or forming a simple vertical structure) are presented and are applied to assessing the Negev vs Sinai differences and the sharp recovery (darkening) of the surface in a Sinai exclosure where anthropogenic pressures were stopped in 1974 by fencing-off the area.

1. Introduction

Man's impact on the Earth's surface was studied as early as the 19th century. In his work, Marsh (1864) discussed soil compaction as the most important result of man's activities. Such compaction is indeed readily observed wherever a footpath crosses a field or a lawn. The influence of compaction on the growth of grass is readily apparent.

It is the thesis of this paper that in arid and semi-arid regions anthropogenic impact over very wide areas results in:

(a) crumbling of the soil, or perhaps in the prevention of natural crusting and cohesion of the surface (strongly influenced by the growth of algae)
(b) a sharp increase in the surface albedo, by a large factor (up to two-thirds). It is by observing the spatial and temporal differences in surface reflectivity/albedo that anthropogenic pressures (and recovery from such pressures) can be monitored.

Surface albedo is the ratio of the solar energy reflected from the surface to that impinging on the surface. It is an important climate-affecting parameter, inasmuch as it affects the earth–atmosphere system albedo and therefore the intake of solar energy by the planet. It also affects the partitioning of the absorption of solar energy between the surface on the one hand and the atmosphere on the other, and therefore atmospheric convection. Surface albedo affects the intake of solar energy at the surface and thus the climate near the ground, influencing schedules of germination, plant growth, and the daily patterns of the activity of animals. Regional differences of albedo influence advection.

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In this paper, the anthropogenic impact on the surface (especially on the surface albedo) in arid regions of the Earth is studied using satellite multispectral imagery and ground-truth observations. The ground-truth observations are limited to the Negev in Israel and the adjoining Sinai, and to Utah in the U.S.A. The study is based on the spatial differences between areas impacted by grazing and other anthropogenic pressures, such as the Sinai, and the protected steppe, where the growth of natural vegetation is not hindered by man and domestic animals. In these arid regions, plant growth is very much moisture-limited. In one case temporal differences are observed and discussed.

In this study, the multispectral and digital character of Landsat imagery are utilized. The Landsat computer-compatible tapes provide radiances to the zenith above a picture-element (pixel) on the surface. Thus, the surface reflectivities that we compute are based on a reflection in one direction only. When such reflectivities are averaged over the solar spectrum, we arrive at a "beam albedo". This limitation and atmospheric effects introduce some uncertainties in the numbers presented.

This study is strongly definitive in a negative sense. The anthropogenic impact on the albedo of the cultivation, overgrazing, and harvesting of the plants in the steppe for firewood and as construction material cannot be described simply as removal of a live canopy of vegetation. Rather the transition is from an exposed "graveyard" of plants (that is an accumulation of dead plants) over a crusted, stable surface in the case of regions protected from impact, to a virtually bare, crumbled soil in the case of severely impacted regions. Many additional studies would be required to fully understand the various aspects of this important process and its consequences.

2. Satellite observations of a natural steppe and impacted areas

Lowman (1969) was apparently the first to discuss the sharp contrast visible from satellites between the bright sands of the Sinai and the dark surface of the Negev. In discussing this effect, Lowman was mistaken in describing the Negev as cultivated fields: the Negev along the Sinai boundary was at that time (and in 1980, still is) a steppe with grasses, low bushes and a few trees. It was not and is not under cultivation. Grazing is limited. Attributing to vegetation the dark appearance of the Negev in this photograph is quite logical, however, since a vegetation canopy over a sandy soil surface is markedly darker than the bare sand itself in the visible range of wavelengths (especially so in the red, where a chlorophyll absorption band lies).

Space photographs from the Gemini and Apollo programs gave stimulus to the development of the Earth Resources Technology Satellite (ERTS) program. The first satellite in this series, now called Landsat 1, was launched in July 1972. From its first operating pass over the Sinai/Negev boundary on October 22, 1972, Landsat produced a series of images showing the area along the boundary with a detail of 60 × 80 m (picture element dimensions). The Landsat Multispectral Scanner System (MSS) provides imagery in two visible bands, but also in two reflective infrared bands:

MSS-4 0.5–0.6 μm, green-yellow
5 0.6–0.7 μm, orange-red
6 0.7–0.8 μm, reflective infrared
7 0.8–1.1 μm, reflective infrared

The surprising finding from the Landsat imagery was that the Negev appeared much darker than the Sinai, with roughly the same contrast (initially estimated by visual inspection) in *all* of the spectral bands (Otterman, 1973). The low infrared reflectivity of the Negev (see Fig. 1) nullifies the possibility that the contrast is due to radiative transfer through a more pronounced live plant cover in the Negev than that in the Sinai. In the spectral range of reflective infrared from 0.7 to 1.1 μm, the radiative transfer characteristics of live plants are very low absorptance and high reflectance and transmittance. The reflectivity is predominantly due to scattering from cell walls in the spongy mesophyll (Gates, 1970). Under such conditions, the reflectivity over a canopy of low optical thickness is about the same as that of the underlying soil and increases with an increasing optical thickness of the canopy. (Myers, 1970; Colwell, 1974; Tucker, 1977). In the case of some succulents, the importance of backscattering from inside the plants is reduced, inasmuch as considerable reflectance occurs at the outermost layer of the thick waxy cuticle of many species. But

Fig. 1. The western Negev and the northern Sinai, part of Landsat image E-2 987-07100, in reflective infrared band MSS-6, 0.7–0.8 μm. The Negev (on the right) and the exclosure (a square area 5.5 × 5.5 km, in the middle) show up as dark in sharp contrast to the bright Sinai (surrounding the exclosure). The Mediterranean Sea is on the left. Approximate scale 1:500 000; October 5, 1977, sun elevation 41.5°.

in any case, the reflectivity is high, because there are no known absorbers active at these reflective infrared wavelengths.

The Western Negev, a triangular area with 60 km long sides, can be described as a vegetated area, but only when compared with the overgrazed Sinai. The moisture-limited vegetation occupies only a small fraction of ground even in the Negev.

Sinai/Negev contrast ratios were computed from digitized radiance levels recorded on computer compatible tables. The ratios were computed from data at three pairs of points,[1] each pair consisting of one point just inside the Sinai and one just inside the Negev. The first pair of points was near where the Sinai, the Negev and the Gaza strip meet, about 14 km from the Mediterranean (annual rainfall about 150–200 mm per year). Pairs 2 and 3 were further from the Mediterranean. The annual rainfall can be roughly estimated as 100–150 mm at pair 2 and 50–100 mm at pair 3. The contrast ratios are presented in Table 1.

The high contrast ratios (in the range of 1.2–1.9) in the bands MSS-6 and MSS-7 should be noted, that is a much lower infrared reflectivity of the relatively protected steppe when compared with an area of inherently the same soil,[2] under the same climatic conditions, but under severe anthropogenic pressure. A Sinai/Negev contrast ratio lower than unity (that is, Negev brighter than Sinai) would be expected in those two infrared bands, because a somewhat larger fraction of the ground is covered by live plants in the Negev, as previously discussed. From these spectral contrasts and from the ground-truth observations it can be inferred that it is the character of the surface in the interstices between the live plants, which are spaced far from each other, that controls the reflectivities. Ground-truth observations, started in the 1972/73 winter, indicate that the surface of the Negev is lightly crusted with an accumulation of dark-grey or dark-brown plant debris. In the Sinai, the surface is crumbled, with little or no discernible accumulation of organic materials. In addition, shadowing effects

[1] Each such point represents a small block of pixels. In each block, six pixels were taken in the direction perpendicular to the scan lines, to average out a possible unequal response of the six detectors in each spectral band.

[2] The crux of the paper is that the characteristics of the soil at the surface are modified, i.e. it is *effectively* not the same soil.

on the interstices by the plants should be considered. A quantitative interpretation of the Sinai and Negev reflectivities based on measurements of terrain component reflectivities, is given in the next section.

Several other Landsat images show an impacted area abutting a protected area. Of these the longest boundary (about 1000 km) is that between impacted Botswana and South West Africa (Namibia). Pronounced contrasts have also been measured across the Afghanistan–U.S.S.R. boundary (from Landsat image E-1341-05520, 29 June 1973) and are listed in Table 1. This area, at the south-eastern fringe of the Kara Kum desert, is quite arid. Afghanistan, near the border, is practically uniformly overgrazed (sheep raising is an important activity) but in the U.S.S.R. overgrazing is localized, only around the settlements (within a 5 km radius), from which the sheep go out daily to graze (Otterman et al., 1976). Contrast ratios are also presented between overgrazed Sahel and a ranch, where grazing is controlled.

Table 1. *Contrast ratios between areas subject to anthropogenic impact and adjacent protected steppe, measured from Landsat digital tapes in various parts of the world*

Band Wavelength (μm)	MSS-4 0.5–0.6	MSS-5 0.6–0.7	MSS-6 0.7–0.8	MSS-7 0.8–1.1
Sinai/Negev 1, 22 Oct 1972	1.55	1.88	1.87	1.73
Sinai/Negev 2, 22 Oct 1972	1.29	1.41	1.41	1.33
Sinai/Negev 3, 22 Oct 1972	1.23	1.30	1.29	1.27
Sinai/Negev 1, 2 Jan 1973	1.49	2.03	1.85	1.69
Sinai/Negev 2, 2 Jan 1973	1.26	1.53	1.43	1.36
Sinai/Negev 3, 2 Jan 1973	1.19	1.24	1.22	1.22
Afghanistan/ USSR 1	1.16	1.21	1.21	1.19
Afghanistan/ USSR 2	1.17	1.22	1.24	1.21
Sahel, Overgrazed/ Ranch, 9 Nov 1972	1.20	1.37	1.41	1.39
Sahel, Overgrazed/ Ranch, 28 Dec 1973	1.15	1.26	1.32	1.29

The Afghanistan/U.S.S.R. contrast ratios in Table 1 are practically identical, in each of the MSS spectral bands, to the Sinai/Negev ratios at pair 2. This strongly suggests that the same processes are at work in both regions, that is the contrast is primarily due to an accumulation of dead plants and debris in the protected steppe on the U.S.S.R. side of the border.

In practically all of the cases in Table 1, the highest contrast ratio occurs in the MSS-5 band, 0.6–0.7 μm. In this band, chlorophyll absorption typically reduces plant canopy reflectivity to the very low values of 0.05 to 0.10. Thus, it is logical to infer that these high contrast ratios in the MSS-5 band are an effect of slightly increased surface cover by the live vegetation in the protected steppe, as compared to the impacted areas. This very small effect is superimposed on the first order effect, which lies in different reflectivity from the interstices as discussed. However, such an inference cannot be regarded as entirely certain, inasmuch as the effect may be due to a dip in the reflectivity of the plant debris, which the measurements described in the next section were not precise enough to detect.

3. Measurements of space and surface reflectivities from Landsat and ground truth measurements

The MSS of Landsat measures the nadir radiance, L_n, in the four spectral bands. This radiance, reported with a 128 digital-count precision (64 counts in band MSS-7), may be expressed as the earth–atmosphere or space reflectivity, a_s, in each band:

$$a_s = \pi L_n / S_\lambda \mu_0, \tag{1}$$

where S_λ is the solar irradiance in the band outside the atmosphere (on a surface perpendicular to the beam) and μ_0 is the cosine of the zenith angle. Inasmuch as S_λ and μ_0 are known much more precisely than L_n, from the measurement point of view a_s is equivalent to L_n.

Otterman and Fraser (1976) studied analytically the relation of a_s to the surface reflectivity a_0. Their conclusion was that for a_0 higher than 0.15, a_s departs by only a few percent from a_0 for a variety of aerosol optical thickness and zenith angle conditions.[1] An exception is found in the MSS-7 band 0.8–1.1 μm, in which absorption by the water vapor reduces the a_s/a_0 ratios to a 0.65–0.90 range, for representative zenith angles and water vapor concentrations. Thus, it appears possible to infer surface reflectivities from the space-measured reflectivities, but there are considerable uncertainties in the MSS-7 band (unless water vapor concentration in a vertical column is measured).

Based on this approach, but using simplified radiative transfer equations developed by Otterman et al. (1980) for low optical thickness conditions, surface reflectivities were derived from the Landsat nadir radiances (calculated from the digital MSS tapes) for the Landsat pass of April 26, 1977. The atmospheric effects on the a_s/a_0 ratios were calculated for an aerosol optical thickness of 0.06 (virtually the same in all the bands), as measured in the Sinai at the time of the satellite passage. In the MSS-7 band calculations, 10 mm of precipitable water in a vertical column was assumed.

The derived surface reflectivities were plotted vs wavelength in Fig. 2. The reflectivities were of the Sinai, the darkest Negev (near the Gaza Strip, close to the Negev point in pair 1 of Table 1), and the average Negev (close to the Negev point in pair 2 of Table 1). Also, Landsat reflectivities of an exclosure in the Sinai are presented. This 5.5 × 5.5 km area was fenced off in the summer of 1974 as an Israeli military base, and can be observed as a darker square in the midst of the bright Sinai in the Landsat imagery (see Fig. 1), starting from 1976 (Otterman, 1977a). Landsat radiances were read in the north-east corner of the exclosure, where there was no construction.

The reflectivities of the darkest Negev were only about 0.6 of those of the Sinai. The reflectivities of the exclosure were about 10% lower than those of the Sinai. All of these four plots (solid lines in Fig. 2) increase monotonically with wavelength. There is no dip in the red, therefore no indication of a measurable surface cover by plants with chlorophyll.

In order to assess quantitatively what components of the surface cover cause the contrast,

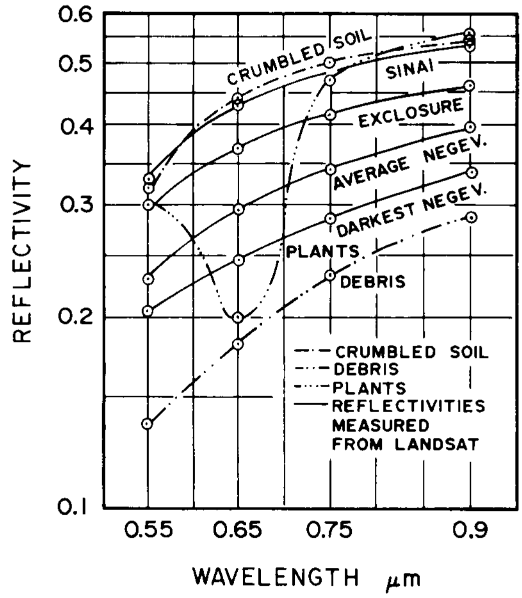

Fig. 2. Spectral reflectivities of the Sinai, exclosure, average Negev and darkest Negev surfaces, calculated from Landsat MSS digital data, April 26, 1977, sun elevation 51°. The reflectivities are plotted against the wavelength of the midpoint of the MSS band (except in band MSS-7, where the reflectivities are presented as pertaining to 0.9 μm, since both the solar irradiation and the MSS detector response decrease sharply beyond 0.95 μm). Spectral reflectivities of the crumbled soil in the exclosure, of the plant debris, and of the young growth of *Artemisia monosperma* placed on the soil in a thick layer, are presented as dotted lines. These three sets of measurements were taken by a hand-held Exotech field radiometer.

in situ measurements were taken of the reflectivity of the crumbled Sinai soil, of the same soil covered by several layers of plant debris, and of young green twigs (tops of twigs only, placed in several layers over soil) of a dominant plant, *Artemisia monosperma*. These measurements were carried out using an Exotech-100 Radiometer, an instrument designed for ground-truth observations in the Landsat programs. By taking a ratio of the radiation reflected from the ground (measured with a narrow view lens) to the impinging radiation (measured with a 2π lens pointed upwards), a spectral reflectivity was derived. The results are also plotted in Fig. 2.

Examination of Fig. 2 indicates that:

(a) The reflectivities of the Sinai, derived from Landsat, are essentially those of bare crumbled

[1] Otterman and Fraser (1976) assumed that the aerosols are non-absorbing. Their conclusion would not be valid for strongly absorbing aerosols. Desert aerosols, however, are apparently nearly pure scatterers (Otterman and Fraser, 1977).

Table 2. *Reflectivities and albedo of the Sinai and the darkest Negev computed from Landsat computer compatible tapes and plant debris reflectivities measured by a ground-truth radiometer*

Band Wavelength (μm)	MSS-4 0.5–0.6	MSS-5 0.6–0.7	MSS-6 0.7–0.8	MSS-7 0.8–1.1	Albedo a_0
Weighing factor for albedo calculation	0.33	0.15	0.12	0.40	—
Sinai reflectivity/albedo	0.33	0.44	0.48	0.54	0.45
Darkest Negev reflectivity/albedo	0.21	0.25	0.28	0.34	0.28
Debris reflectivity/albedo (K. T. Balakrishnan)	0.14	0.18	0.24	0.27	0.21

soil, as measured in situ by the ground-truth radiometer. The reflectivity in the infrared is very high, about 0.55.

(b) The young growth of the prevalent bush, *Artemisia monosperma*, also has a high infrared reflectivity of about 0.55.

(c) The reflectivity of the Negev is not due to the spectral signature of *Artemisia*. The *Artemisia* plot shows the expected dip[1] in MSS-5, but such a dip is absent in all of the reflectivities derived from Landsat.

The Landsat MSS bands cover the wavelengths from 0.5 μm to 1.1 μm, and there is no information about nadir radiances outside this range, where an appreciable fraction of the solar irradiance lies. Assuming that the reflectivity below 0.5 μm is the same as in band MSS-4, and the reflectivity above 1.1 μm is the same as in band MSS-7, and further assuming a distribution of the solar irradiance at the ground level as tabulated in the *Handbook of Geophysics* (1961) for an air mass of 2 and for 20 mm water vapor in a vertical column, then the weighing factors for the four bands used in computing the albedo are as given in Table 2. It should be noted that the weighing factors for the two infrared bands add up to 0.52, indicating the importance of this part of the spectrum.[2] The albedo of the Sinai derived by this approach was 0.45 and of the darkest Negev was 0.28, a difference of 0.17 (61% of the albedo of the darkest Negev). The albedo of the plant debris (1978 measurements using the Exotech-100 in the Sinai and at the Tel Aviv University, by K. T. Balakrishnan) was 0.21.

[1] The reflectivity of *Artemisia* measured in band MSS-5 is much higher than is typical for a thick canopy. Apparently, the *Artemisia* twigs did not constitute an optically thick layer.

[2] Otterman and Fraser (1976) pointed out that the difference between the values of sandy desert albedo which they derived and the much lower previous measurements, might be explainable if the previous measurements did not properly include the infrared wavelengths.

4. Conclusions and discussion

Based on the spatial differences between impacted areas and the adjoining protected steppe (Tables 1 and 2, and Fig. 2) it is concluded that anthropogenic pressures can result in an increase of albedo by a factor of two-thirds, or by nearly 0.2. The effect can be much greater than that postulated by Schneider and Dickinson (1974) who estimated that anthropogenic impact can increase the albedo by 10% of its value.

Only a small change in albedo can be produced by simply removing the plant canopy, when the soil reflectivity is the same with or without the canopy. A removal of the canopy decreases the infrared reflectivity and increases the visible reflectivity (especially the red reflectivity) of the surface. Over a very bright soil, an overall increase in the albedo results. The magnitude of the increase can be assessed from Fig. 2 by comparing the reflectivity of bare soil with the same soil covered by *Artemisia* tops. A reasonable estimate in this case is an increase in albedo of 10%. Over a darker soil, the reduction of infrared reflectivity outweighs the increase in the visible reflectivity, and an overall reduction in the albedo results.

Such an albedo reduction, resulting from grazing in a region of high rainfall in Australia, was reported by Duggin et al. (1975). In this region, plant growth was not moisture-controlled, and a thick plant canopy covers most of the ground (90 to 100%). Under such conditions, any change in soil surface characteristics, if it occurs at all, does not materially affect the reflectivity. In arid regions, however, which are the subject of this study, the albedo increase is primarily due to a change in the surface characteristics from the debris covered crusts in a protected ecosystem to the crumbled by trampling soil in an impacted area. In the darkest Negev, the fraction of the surface covered by the debris is estimated to be 0.55 (see Section 5). An additional effect that causes a darkening of the protected steppe stems from shadowing by the bushes or clumps of grass that are widely separated from each other. This shadowing effect is probably small in the Negev, but is thought to be dominant in the exclosure. These shadowing effects are discussed in Section 5.

In the general area of Sinai/Negev, pairs 1 and 2, the surface shows no accumulation of pebbles. In the vicinity of pair 3, small accumulation is encountered. In other arid regions (including also large parts of the Negev and the Sinai) such an accumulation can be quite pronounced, leading to the formation of a desert pavement. On such terrain, the hoofs of grazing animals tend to push the pebbles into the soil, decreasing their accumulation on the surface. Such a decrease was observed in a grazed area in Utah which adjoins an exclosure where no grazing occurred during the last 40 years. Inasmuch as the pebbles are darker than the soil and introduce some shadowing, their accumulation causes an ungrazed area to be darker than a grazed area. This effect can also be expected in plowed areas.

Such a large increase of albedo by nearly 0.2 as in the case of the Sinai vs the Negev, can occur only over inherently very bright soils, with an albedo of 0.45 when crumbled. Over darker soils, the impact will be reduced in magnitude. Comparing pairs 1, 2 and 3 along the Sinai/Negev boundary, one can tentatively conclude that the magnitude of the change in the albedo, the Δa_0 effect depends on rainfall amounts: if rainfall is less than 200 mm/year, the effect is reduced, apparently because the crusting and accumulation of debris, and therefore the darkening, are all reduced. When the rainfall exceeds 600–800 mm/year, the canopy covers most of the ground and, as was explained, the impact on the albedo is small.

Based on the studies of the Sinai exclosure, it is concluded that the anthropogenic impact on the albedo is reversible. The darkening proceeds rather quickly when the pressures are removed. In the span of less than 3 years, a reduction in the albedo by $\Delta a_0 = 0.05$ occurred. This change is about one-third or one-half of the expected darkening when the steady-state, protected steppe albedo is reached (assuming respectively that the exclosure when fully recovered will become as dark as the darkest Negev or the average Negev; inasmuch as the amounts of rainfall and the soils are not the same in these locations, such extrapolation is uncertain). The Negev, where the anthropogenic pressures sharply subsided after the 1948/49 war, apparently has reached its "steady-state" albedo. Two years after the exclosure was formed, not only did the albedo move rapidly towards the status of the protected steppe, but also the flora increased both in the numbers of plants and in numbers of species (Otterman et al., 1978). It is uncertain, however, whether all the species in the original "virgin" steppe will reappear and whether the ecosystem will revert to its virgin state, that is, to the prehistoric ecosystem which existed before the onset of the anthropogenic pressures.

Inasmuch as surface characteristics have an important bearing on our climate, and in arid regions the anthropogenic impact can change surface characteristics quite drastically, there is a need to further study the processes of anthropogenic impact and recovery. Parameterization of surface/atmosphere interaction in the computer simulation of large-scale atmospheric circulation can become meaningful only if in-depth studies are conducted of the albedo and other parameters, such as thermal properties of the soil, surface roughness and evapotranspiration. Such studies should relate to the actual ecosystems, in different seasons, under specific climatic conditions.

Another direction which requires further studies, is the geographical extent of the various ecosystems in the arid and the very arid climate zones such as the protected steppe, impacted steppe, and sandy desert. Otterman (1977b) attempted to estimate the increase in global surface albedo from the prehistoric times to the present—and concluded that the surface albedo now is about 0.154 as compared to 0.141 6000 years ago. However, Otterman (1977b) probably overestimated the total area of impacted steppe and sandy desert. Satisfactory information on this question is not available, but could be obtained by appropriate processing of multispectral radiometry data from satellites such as Landsat. In such a program, changes may be monitored that are caused by an increase in the severity of impact on one hand, or by recovery when the anthropogenic pressures are removed, on the other.

5. Appendix

A simple model of the effect of dead plants on reflectivities can be constructed assuming that pieces of the plants, the debris, lie on the surface, without protruding above it. In this planar (horizontal) model, let h be the fraction of the ground covered by the debris, r_d reflectivity of the debris, and r_i the reflectivity of the bare soil. The nadir (beam) reflectivity r_n is then simply the proportional average of r_d and r_i:

$$r_n = r_i(1 - h) + r_d h \qquad \text{(A-1)}$$

This simple model is a reasonable approximation of the reflectivity of the Negev. This follows from:

(a) ground-truth observations that in the Negev the dead plants are predominantly found in small pieces scattered on the surface, and

(b) that the contrast ratio Sinai/Negev varies only weakly as a function of the solar elevation angle, indicating that the shadowing effects associated with a non-planar structure (see later discussion) are not predominant.

Assuming that eq. (A-1) holds and furthermore assuming that on the darkest Negev surface interstices between pieces of debris consist entirely of lightly crusted soil with spectral reflectivities equal to 80% of the reflectivities of the crumbled soil[1] (based on measurements in the Negev close to the Sinai/Negev boundary), the fraction h of ground cover by debris is calculated to be about 0.55. However, there is considerable spread in the values of h as calculated for the four bands, as can be expected from the imprecise nature of the reflectivity measurements and the approximate character of eq. (A-1).

[1] There is pronounced variability between various crusts. Some crusts are darker than the crumbled soil by a factor of two.

Even a cursory inspection of the Sinai exclosure indicates that eq. (A-1) would be inappropriate for studying the Sinai/exclosure contrast, because dead bushes (especially those of a variety of sage-brush, *Artemisia monosperma*) remain intact in situ in the exclosure and constitute the predominant difference from the surrounding impacted area. The reasons for this difference between the exclosure and the Negev, where plant debris in small pieces dominate, are not clear. The difference might be linked to the total absence of anthropogenic impact in the exclosure (along its perimeter and in its north-east corner) since 1974—while in the Negev, there is limited grazing and gathering of plants for firewood and the construction of fences. Possibly, the gathering of plants in the Negev prevents an accumulation of dead bushes, except when broken into small pieces.

An approach for computing reflectivities as a function of the ground cover by bushes and tussocks was developed, with a view to serving as a relevant treatment for the exclosure. The surface is assumed to be a structure of cylindrical stalks, placed perpendicularly to a horizontal plane of soil. The reflectivity of the stalks is denoted r_d and of that of the soil in the interstices between the stalks, r_i. Both components of the surface are assumed to reflect according to the Lambert law. The height of the stalks is much larger than the diameter, so that the reflections from the circular ends of stalks are neglected. A dimensionless parameter s denotes the fractional ground cover if the stalks were to lie on the ground, i.e., it is the product of diameter, height and number of cylinders per unit area. Considering only the direct solar radiance at a zenith angle of θ_0, $s \tan \theta_0$ is the fraction of the horizontal surface that is shadowed, that is, the fraction of the irradiance from the direct beam that is intercepted by the stalks. Half of the first reflection from the stalks, $r_d s \tan \theta_0/2$, irradiates the interstices, if the stalk-to-stalk spacing is much larger than the height of stalks, that is, if the reflections among the neighbouring stalks are not significant. Neglecting higher order reflections, the nadir reflectivity is

$$r_n = r_i \left[1 - s \tan \theta_0 \left(1 - \frac{r_d}{s}\right)\right] \qquad \text{(A-2)}$$

This equation reproduces the known effect of a three-dimensional structure, a reduction in the nadir reflectivity which depends on the solar zenith angle. For $s \tan \theta_0 > 1$, the model indicates that 100% of the interstices are shadowed and eq. (A-2) can yield negative reflectivities. In a more sophisticated model, overlapping of shadows is considered, and $s \tan \theta_0$ appears as an exponent rather than a linear term (Otterman, 1980).

Assuming that (i) the reflectivity of the surface in the exclosure between the dead bushes, r_i, remains like that of the Sinai, as measured from Landsat, and (ii) the reflectivity of the dead bushes, r_d, is the same as the reflectivity of debris gathered from the surface as measured by Balakrishnan, see Fig. 2 and Table 2), one can compute the fraction s using eq. (A-2). For the April 26, 1977 pass, $\tan \theta_0$ is 1.235, and in MSS-7 $r_n = 0.37$, $r_i = 0.44$ and $r_d = 0.18$ (from Fig. 2). We thus have

$$s = \frac{1 - (r_n/r_i)}{\tan \theta_0 [1 - (r_d/2)]} = \frac{1 - (0.37/0.44)}{1.235 [1 - (0.18/2)]} = 0.14$$

Repeating the calculation for the other bands we obtain these values of s: for MSS-6, 0.13; for MSS-5, 0.14; for MSS-4, 0.08. The fraction s represents equivalent ground cover fraction for the vertical structure and basically is the same in all the bands.[1] Our calculations are satisfactorily repeatable in three bands, but in MSS-4 the computational result does not fit the results in the other bands.

The general problem of monitoring impact/recovery is very complex, since the effects of debris strewn on the horizontal surface (the h fraction) and of the dried or dead plants remaining in situ, as predominantly vertical structures (the s fraction) might have to be considered simultaneously. However, if data are available for different seasons of the year, at different solar elevations, and assuming that neither the s fraction nor the h fraction changes materially during the year, it is possible to separate the two effects, since the s effect is multiplied by $\tan \theta_0$, becoming the dominant effect in winter months.

Occasional increases in soil moisture or in the live vegetation component after rains complicate the determination of s and h.

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[1] The parameter s is a measure of shadowing for the direct as well as for the scattered irradiance. When s is computed, as above, considering only the direct irradiance, the results can be expected to be somewhat different in the various bands. In MSS-4 the Rayleigh scattering (and therefore the nearly isotropically scattered component of the irradiance) is stronger than at the longer wavelengths. Thus, at solar angles close to the zenith, s computed by eq. (A-2) will be somewhat higher in MSS-4 than in the other bands, inasmuch as the shadowing effect for the scattered irradiance is stronger than for the direct beam. Converse is true at low solar elevations. However, at $\tan \theta_0$ of 1.235 the differences between MSS-4 and the other bands should have been very small.

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СПУТНИКОВЫЕ И ПОЛЕВЫЕ ИССЛЕДОВАНИЯ ВОЗДЕЙСТВИЯ ЧЕЛОВЕКА НА ЗЕМНУЮ ПОВЕРХНОСТЬ В АРИДНЫХ ОБЛАСТЯХ

В аридных областях с песчаными почвами как степи, свободные от избытка антропогенных воздействий, так и более яркие области, подвергаемые таким избыточным воздействиям, имеют коэффициенты спектральной отражательной способности (получаемые из спутниковых радиометрических данных), увеличивающиеся с длиной волны (от зеленого до отражающей инфракрасной области спектра). Падение отражения в красной области, характерное для всех растений, содержащих хлорофилл, здесь отсутствует. В экосистеме степи, не подверженной влиянию человека, почва устойчива и комковата. Отмершие растения или остаются на месте, или распределяются в виде остатков на поверхности. Коэффициенты спектральной отражательной способности (получаемые на спутниках) могут быть представлены в виде взвешенных средних отражательных способностей почвы и остатков растений (измеренных в поле ручным радиометром). В областях, подверженных влиянию человека, спектральные отражательные способности поверхности (полученные из спутниковых данных) практически совпадают с таковыми для раскрошенной голой почвы (определенными ручным радиометром). Аккумуляция органического материала мала. В таких областях резкое увеличение альбедо вызвано антропогенными воздействиями (от 0,28 в случае защищенной пустыни Негев до 0,45 в случае прилегающей подверженной воздействию Синайской пустыни). Это различие в альбедо нельзя объяснить прямым удалением живой растительности, а происходит оно, главным образом, из-за аккумуляции отмерших растений на комковатой почве в защищенной степи и из-за отсутствия такой аккумуляции в областях, подверженных влиянию человека. Представлены модели отражения в надире в виде функции частичного покрытия почвы растениями или их остатками (рассеянными по поверхности, или формирующими простую вертикальную структуру). Эти модели используются для объяснения различий между Негевом и Синаем и резкого восстановления альбедо (потемнения) поверхности на Синае в области, где антропогенные воздействия были прекращены в 1974 г. путем огораживания этой области.