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Ecosystem Management of Desertified Shrublands in Israel

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Abstract

The objectives of this study were to understand the ecological processes and possible management strategies in desertified shrublands. We hypothesized that biological production and diversity in desertified shrublands in the Negev in Israel are low due to water, soil, and nutrient leakage from the ecosystem. We designed a series of field experiments in order to examine (a) whether source–sink relationships exist between the crusted soil and the shrub patches, (b) whether resources (water, soil, and nutrients) leak from the system, and (c) whether management, which changes the landscape mosaic by introducing new sink patches that reduce leakage of resources, may increase productivity and diversity. The results indicate that the low number of shrub patches, which serve as sinks for resources, leads to water, soil, and nutrient leakage from the ecosystem. This leakage reduces ecosystem production and diversity. We found that artificially created pits, which act as sinks for resources, decrease leakage and increase biomass production and annual plant species diversity. Based on the experimental results, we developed conceptual models for shrubland desertification and ecosystem management. The models are based on a source–sink relationship between two patch types characteristic of shrublands. The models relate landscape productivity to the number of sink patches and suggest that, in cases where there are too few sinks, artificially created sink patches should be added. Management methods were developed to reduce resource leakage in the desertified shrubland of the Negev. Methods included construction of man-made pits in the landscape that add resource-enriched patches to the landscape. These patches are used to create parks consisting of clusters of trees integrated into a matrix of shrubs and herbaceous vegetation. The managed parks are used for recreational purposes and for rangeland.

Key words: desertification; ecosystem leakage; ecosystem management; microphytic soil crust; Negev; shrubland; surface runoff.

Introduction

The search for ecosystem management methods in desertified ecosystems is an issue that engrosses researchers and managers of drylands (Graetz 1991; Hoekstra and Shachak 1996). Understanding the processes limiting production and diversity in these landscapes is essential for the successful management of desertified landscapes (Schlesinger and others 1990; Thomas 1995).

We assume that shrubland production and diversity in the Negev, Israel, are not limited by lack of resources, but by resource availability to organisms. We propose that some water and nutrient resources are not available to organisms because they leak from the ecosystem before they can be used. This assumption is based on the structure of dry shrubland ecosystems that consist of crusted and shrub patches.

Patchiness is conspicuous in shrublands, where shrubs are often interspersed in a matrix of shorter plants (Noy-Meir 1985). This patchiness can be the result of limited amounts of water incapable of

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supporting a large cover of shrubs (Tongway and Ludwig 1994) or as a consequence of overgrazing, converting semiarid grasslands into shrublands (Schlesinger and others 1990). In shrublands, the small-scale landscape mosaic is comprised of two patch types. One is dominated by vascular plants (shrub patches) and the other by a nonvascular microphytic community (crust patches) (West 1990). Shrub patches are the principal loci of productivity and diversity, mainly because of the accumulation of water and nutrients that promote the growth of rich herbaceous vegetation under the shrubs (Weinstein 1975; Noy-Meir 1985; Garner and Steinberger 1989; West 1989; Allen 1991; Schlesinger and others 1990; Boeken and Shachak 1994; Zaady and others 1996a).

In many dry shrublands, there are functional source–sink relationships between the two patch types. Usually, the crust patches are sources for soil materials and runoff water, whereas the shrub are sinks (Yair and Shachak 1987; Rostango 1989; Snow and McClelland 1990; Stockton and Gillette 1990; Abrahams and others 1994, 1995; Eldridge and Greene 1994).

We propose that in a shrubland composed of crust and shrub patches, such as the Negev, we can distinguish between natural and disturbed states. In a natural state, the arrangement of the landscape mosaic is such that resources generated by the crust patch are intercepted by and accumulate in the shrub patches. In this case, the source–sink relationship between the two patch types is critical to the functioning of the system. The relatively high production of the shrub patch is determined by the input from the crust patches (Boeken and Shachak 1994). In a disturbed state, human activities, such livestock grazing and clear cutting for firewood, reduce the abundance of shrub patches in the landscape (Bruins 1990).

In this article, we proposed to test the hypothesis that under disturbed conditions the resources generated by the crust patches leak from the system because there are not enough shrub patches to intercept the flow. The net effect of shrub patch reduction is lower resource availability and less production in relation to the undisturbed state.

The objectives of this article are (a) to demonstrate that under present conditions there is a leakage of water and nutrients from the dry shrubland ecosystem in the Negev, (b) to describe ecosystem responses to the reduction of resource leakage, and (c) to report on ecosystem management methods that are used in the Negev to reduce the leakage of ecosystem resources and to increase production. In addition, we present a conceptual model of dry shrubland desertification and principles for ecosystem management of desertified shrublands.

Methods

The Research Site

We investigated the relationship among patchiness, ecosystem processes, and the impact of management in Sayeret Shaked Park, in the northern Negev, Israel. The park receives an average annual precipitation of 200 mm. In this area, as in most of the Negev, most of the vegetation production and diversity are determined by annual herbaceous plants (Evenari and others 1983). The landscape mosaic (Pickett and White 1985) is characterized by a matrix of soil crust, covered with a microphytic community, and small patches of dwarf bushes, mainly *Noaea mucronata*, *Atractylis comosa*, and *Thymelaea hirsuta*. The microphytic matrix is composed of cyanobacteria, bacteria, algae, bryophytes, and lichens (McIlvanie 1942; West 1990). The surface of the soil crust is flat and solid (Fletcher and Martin 1948), because of adhesion of soil particles by polysaccharides, excreted mainly by cyanobacteria and bacteria.

Patches of dwarf bushes—shrub patches—differ in their characteristics from crust patches. Shrub patches are characterized by loose soil mounds covering an area of 1,000–30,000 cm^2, which are rich in nutrients and organic matter. Shrub patch nutrients come from litter decomposition and animal excretions (Zaady and others 1996b).

Experimental Studies

We designed a series of field experiments in order to examine (a) whether a source–sink relationship exists between the crusted soil and the shrub patches, (b) whether resources (water, soil, and nutrients) leak from the system, and (c) whether management, which changes the landscape mosaic by introducing new sink patches that reduce leakage of resources, may increase production and diversity.

Source–sink relationships and leakage on small scale.

We used five 1.0×0.5-m experimental units containing only a crust patch and five units containing both shrub and crust patches. We constructed 10 experimental units along a hill slope, with the 1.0-m side of each unit parallel to the slope and with the crust patch upslope from the shrub patch. The shrub patch occupied approximately one-third of the area of each experimental unit. The units were surrounded by a 12-cm-high PVC wall, sunken approximately 5.0 cm into the ground. Downslope from each unit was a covered runoff collection box that funneled the unit's runoff, or leakage, into a 10-L underground storage tank.

After each runoff event, we measured the volume of water collected in the underground storage tank, which represented the water leakage from the system. Soil erosion was measured by sediment collection in the runoff collection box; runoff water was filtered out. Nitrate concentration was determined by colorimetric analysis with an Alpkem continuous flow analyzer (Shachak and Lovett 1998).

Patchiness, scale, and water leakage. Larger-scale PVC enclosed units (6 × 15 m), with a network of shrub patches in a crust matrix were set up to examine the water leakage from a natural slope (four units) and a manipulated slope (three units). Manipulation consisted of scraping the shrub patches to remove the shrubs and associated soil mounds. Scraping was done mechanically by a tractor with a grader. In addition, we constructed three enclosed units (5 × 5 m) and another three units (5 × 15 m) to test whether water leakage is spatial scale dependent. The units were surrounded by 20-cm-high walls. We measured the amount of runoff generated by each unit after a rainfall event for 2 years.

Regression analysis (Superanova; SAS Institute, Cary, NC, USA) was used to compare water leakage at various scales. Each point on the regression plane refers to water leakage during the same rainfall event.

Responses to ecosystem management: soil moisture. We measured soil moisture in contour catchments, the most common method used in ecosystem management in the Negev. Contour catchments are rows of pits constructed parallel to each other along altitudinal lines on the slopes. Contour catchments are located in areas with deep to shallow stony soil and collect and absorb runoff water, organic matter, and nutrients flowing downhill on the surface. The accumulated supplementary materials enable the development of trees and herbaceous plants. The arrangement of the terraces can be designed to allow changes in runoff and storage volume in accordance with the variability in the amount of runoff generation in time and space. Earthen barriers, arranged vertically to the contour catchments, assure unified distribution of runoff. Contour catchments are constructed mechanically (by bulldozers and graders). We measured the soil moisture before the rainy season and after the first rain by using neutron probes. Field calibrations were made by comparing neutron readings from an access tube installed in the field with volumetric water content values determined gravimetrically immediately adjacent to the tube (Bell 1976). Aluminum access tubes (diameter, 50 mm, and width, 5 mm) were installed to depth of 350 cm, down which the neutron probes could be lowered. We measured the soil moisture in six contour terraces and six undisturbed areas to the soil depth of 350 cm (every 20–30 cm).

Natural vegetation. We examined the effect of leakage reduction on the production and diversity of annual vegetation in hill-slope minicatchments. Hill-slope minicatchments are pits for runoff-water collection with storage volumes of up to several dozen liters. The pits are dug on hill slopes where soil cover is limited. This is generally on the upper slope or the midslope. The pits create sinks for resources and seeds. Hill-slope minicatchments are constructed manually and only when the construction of contour catchments is not possible because of a steep slope gradient.

In April (peak biomass), we harvested all of the herbaceous plants from seven hill-slope minicatchments (100 × 23 × 30 cm) and from seven undisturbed microphytic soil crust plots adjacent to each minicatchment. We identified the species and oven dried the plants for dry biomass determination. We used a paired t test to evaluate the significance of annual plant responses to hill-slope minicatchment construction.

Planted trees. To examine the effect of hill-slope minicatchment construction on planted trees, we selected a hill slope in an area of about 92-mm average annual rainfall (about 50 km south of the study area). Studies showed that, in this area, rainfall can not support tree growth on the hill slope (Evenari and others 1983; Yair and Shachak 1987). We constructed 17 hill-slope minicatchments in 1982 and planted a *Callitris verrucosa* seedling in each minicatchment. We selected *C. verrucosa* because it is relatively easy to estimate growth rate by measuring height. This is due to the similarity in the morphology of individual trees. We monitored tree growth from 1983 to 1997.

Results

Source–Sink Relationships and Leakage on a Small Scale

For all rain events that produced runoff, water leakage was significantly higher [repeated-measures analysis of variance (ANOVA): $F1{,}8 = 78.413$, $P = 0.003$] from plots covered only by crust than from plots supporting both crust and shrub patches (Figure 1a). The annual average runoff for plots covered by crust alone was 36.2% of the water input by rain, while runoff from the mixed patch plots was 9.1%. Comparison of runoff generation

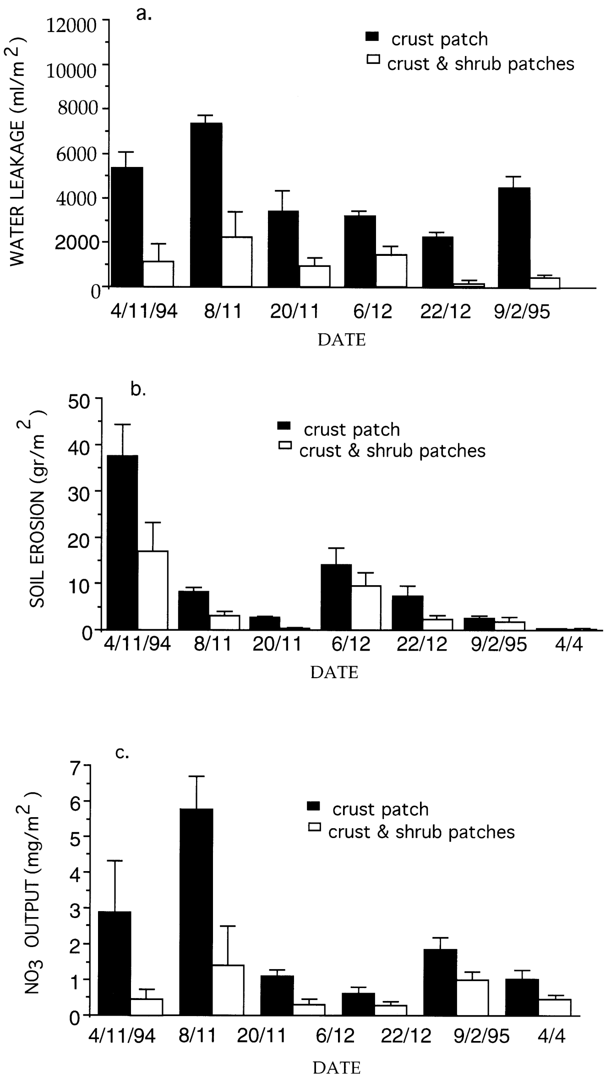

Figure 1. Water (a), soil (b), and NO_3 (c) leakage from unipatch (crusted soil) and dual-patch (crusted soil and shrub) systems. The shrub patch is located at the lower part of the system and occupied 33% of the area.

between plots with and without shrub patches shows a significant correlation between the runoff events ($y = 23.1{+}0.24x$; $F1,9 = 23.208$, $P = 0.0009$). However, the presence of a shrub patch in 30% of each experimental treatment reduced leakage disproportionately by 75%.

There were similar decreases in soil erosion and NO_3 leakage due to the sink function of the shrub patch (Figure 1b). Soil erosion was reduced by 50% in plots containing shrub patches (Figure 1c) even though the loose soil beneath shrubs is potentially easily eroded. NO_3 leakage in runoff was reduced 80% by the presence of a downslope shrub patch. The difference is significant for both soil erosion and NO_3 output (repeated-measures ANOVA: $F1,9 = 8.347$, $P = 0.02$ for soil erosion; and $F1.9 = 11.767$, $P = 0.04$ for NO_3 output).

Three trends emerge from these results: (a) the interaction between rainfall and crust patches causes a downslope movement of water, soil, and nutrients from those patches; (b) a portion of the water, soil, and nutrients that leaks from the upslope crust patch is absorbed by the downslope shrub patch; and (c) a system that includes a crust patch with 70% surface cover and a shrub patch with 30% cover will leak. Thus, the shrub patches are not able to absorb the flow of resources from source crust patches when the two are in a ratio of 1:2. The results from this fine-scale study support the hypotheses that (a) in drylands having a two-phase patch array, microphytic crust acts as a source patch, while shrubs and their associated biotic and physical environment act as sink patches, and (b) when the sink function of the shrub patches is lower than the amount of resources flowing from source patches, the ecosystem leaks.

Patchiness, Scale, and Water Leakage

We wanted to determine whether there was a relationship in water leakage between different-sized areas. We regressed small-scale runoff leakage (0.5 m^2, two patches only, with a ratio of 3:1 for crust/shrub patches) against large-scale runoff (60 m^2, with about 36 shrub patches and a ratio of 5:1 crust/shrub patches) for eight runoff events (Figure 2a).

There is a high and significant correlation between the two scales of runoff generation (df 1,7, $F = 205.186$, $P = 0.0001$, $R^2 = 0.967$). However, the leakage from the larger plots is greater. On average, the ratio of rainfall to runoff is 1.26 greater. This can be attributed to the higher ratio between the runoff source and sink (that is, the crust/shrub ratio) in the larger plots. The effect of sink removal is shown by the correlation of the runoff generated by the scraped plots (removal of all shrubs and underlying mounds) and the undisturbed plots (Figure 2b). There is a high and significant correlation between runoff generation from the undisturbed plots and from the scraped plots (df 1,7, $F = 62.154$, $P = 0.0002$, $R^2 = 0.912$). Percent runoff was about 7% higher for each runoff event when the shrubs and soil mound were removed.

The results from the large-scale study indicate that (a) in the Negev, under present conditions, the landscape, composed of crust and shrub patches, leaks; and (b) the leakage of water is related to the number of shrub patches that function as sinks for water.

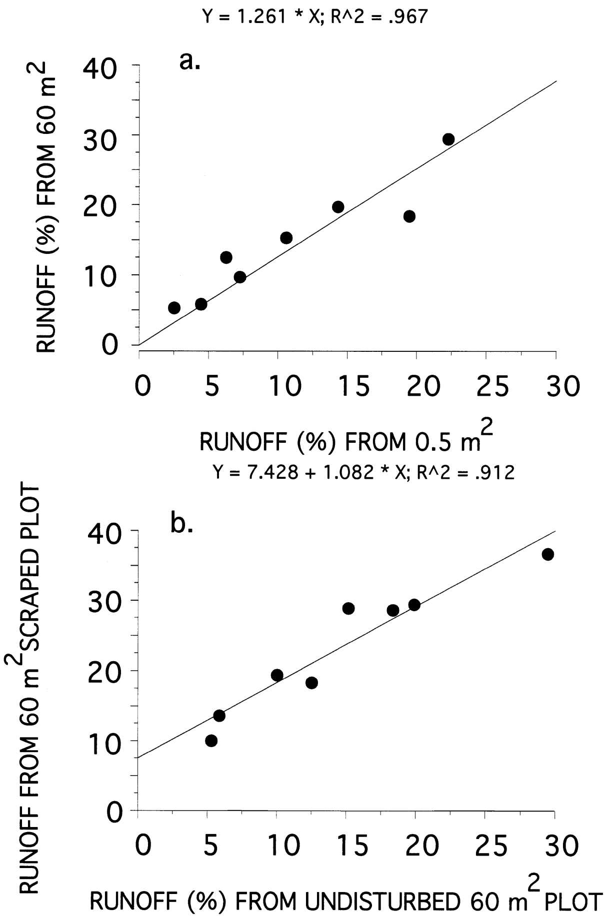

Figure 2. (a) Runoff water production in relation to scale a and disturbance. (b) Percent runoff is the ratio between runoff and rainfall amount for the same unit area.

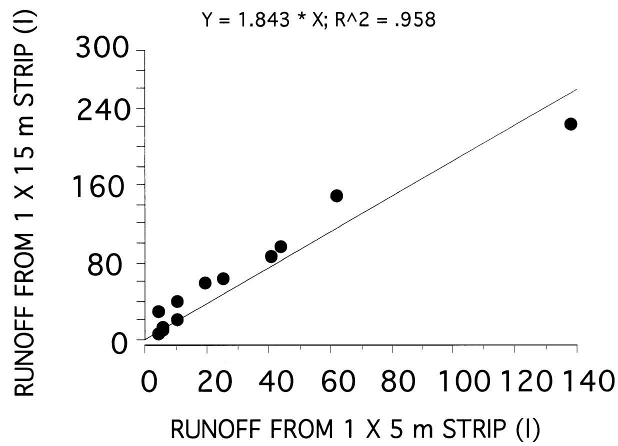

Figure 3. Spatial scale and runoff leakage.

Scale and Man-made Sinks

To understand the effect of spatial scale on runoff collection in man-made sinks such as contour catchments and hill-slope minicatchments, we regressed runoff leakage from the same slope with different slope lengths (Figure 3). Two trends can be seen: (a) There is a significant correlation between runoff leakage from slope lengths of 5 and of 15 m (*df* 1,11, $F = 763.955$, $P = 0.0001$, $R^2 = 0.986$). (b) Despite the threefold increase in area (from 5 to 15 m^2), runoff leakage increased only about 1.8 times. This implies that the amount of water collected in contour catchments and hill-slope minicatchments should increase with the increased distance between the two adjacent man-made sinks along the slope. However, the amount of water collected per unit area should decrease.

Responses to Ecosystem Management

Soil moisture. Figure 4 demonstrates the effect of contour catchments on soil moisture. At the end of the dry season (April–November) at each soil depth measured, soil moisture is significantly higher in the contour catchments than in the untreated area (paired *t* test, *df* 30, $t = 8.728$, $P = 0.0001$). After the first runoff generating rainfall, in December, the average percent soil moisture in the contour catchments increased from 19% to 31%. The increase at each soil depth is significant (paired *t* test, *df* 15, $t = 15.965$, $P = 0.0001$). In the undisturbed area, water infiltrated only to about 25 cm. The differences in soil moisture from depths of 50–350 cm in the undisturbed area were not significantly different than before the rains (paired *t* test, *df* 13, $t = 1.672$, $P = 0.1185$). These results indicate that adding a man-made sink function by construction of pits can (a) reduce water leakage and (b) store large amounts of water as soil moisture that persists throughout the dry season.

Natural vegetation. Management practices such as building hill-slope minicatchments in the microphytic soil crust affected biomass production and diversity of annual plants (Figure 5). Biomass production was significantly higher in the hill-slope minicatchment pits than in the unmanipulated microphytic crust (paired *t* test, *df* 6, $t = 5.959$, $P = 0.0014$). Biomass was about 10 times greater in the hill-slope minicatchment than in the adjacent crust. Species richness of vegetation in the pit was also significantly greater than on the crust (paired *t* test, *df* 6, $t = 5.603$, $P = 0.001$). Species numbers in the pits were about threefold greater as a result of the disturbance and reduction in leakage from the microphytic crust.

Planted Trees

Our results show that construction of sinks in a leaking ecosystem, in an area with only 92-mm average rainfall per year, can support a continuous growth of trees (Figure 6). During the past 15 years,

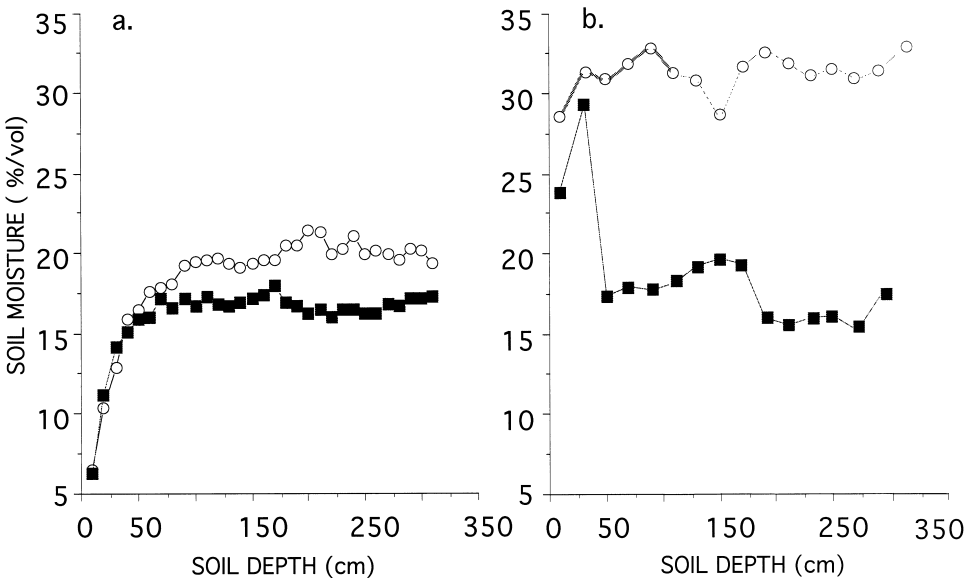

Figure 4. Soil moisture in unmanaged (solid squares) and in contour catchments (open circles) (a) at the end of the dry season and (b) after the first rain.

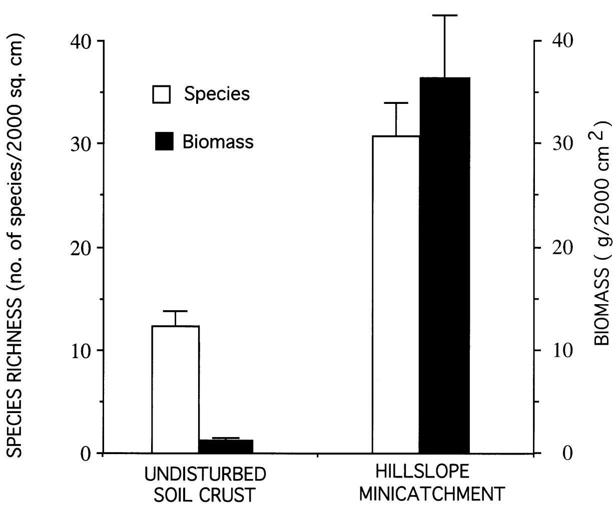

Figure 5. Species richness and biomass production of annual plants on undisturbed soil crust and in water enriched hill-slope minicatchment.

Callitris verrucosa trees planted in hill-slope minicatchments grew, on average, from 30 to 260 cm. This is in spite of a number of low rainfall years (5 of the past 15 years were drought years).

Discussion

A Model of Shrubland Desertification

In a shrubland composed of crust and shrub patches, such as the Negev, we can distinguish between natural and disturbed states. In the natural state, the landscape mosaic is arranged such that resources generated by the crust patches are intercepted by and accumulate in the shrub patches. The crust patches are sources for soil materials and runoff water (Rostango 1989; Yair and Shachak 1987; Snow and McClelland 1990; Stockton and Gillette 1990; Eldridge 1993; Abrahams and others 1994, 1995). Shrub patches are sinks and the principal loci of productivity and diversity due to the accumulation of soil, water, and nutrients that promote rich herbaceous vegetation growth under the shrubs (Weinstein 1975; Noy-Meir 1985; Garner and Steinberger 1989; Shachak and Lovett 1998; West 1989; Schlesinger and others 1990; Allen 1991; Boeken and Shachak 1994; Zaady and others 1996). Under natural conditions, the source–sink relationship between the two patch types is critical to the functioning of the system. Source–sink relationships are not unique to shrublands. Similar situations have been described for Australian landscapes (Ludwig and Tongway 1995).

Human activities, such as livestock grazing and clear cutting for firewood, disturb the landscape, reducing the abundance of shrub patches (Bruins 1990; Ludwig and others 1997). We found that the reduction in the number of shrub patches reduced the sink strength of the ecosystem and therefore increased leakage. The increased leakage of resources and decreased production resulting from shrub patch destruction and crust patch expansion are recognized as shrubland desertification (Shachak and Lovett 1998).

Within the framework of the source–sink relationship between the two patch types, our conceptual model on the relationships among shrub patch destruction and desertification is as follows: In arid shrublands, as a result of low amounts of precipita-

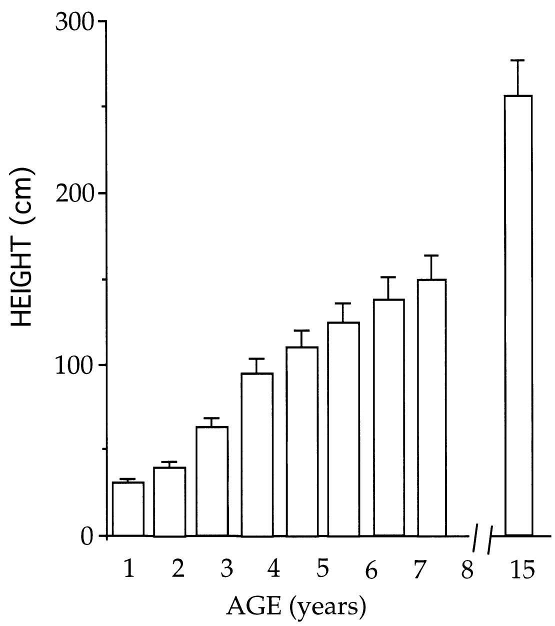

Figure 6. Growth of *Callitris verrucosa* trees planted in hill-slope minicatchments in the central Negev (90-mm mean annual rainfall).

tion (Tongway and Ludwig 1994) or as a result of grassland overgrazing (Schlesinger and others 1990), development of landscape mosaics results in crust and shrub patches. The relationships between crust and shrub patches are determined by the location of the ecological system on the precipitation gradient. There is an inverse relationship between annual precipitation and the crust-to-shrub cover ratio (Shachak and others 1997). The ratio between crust and shrub cover, which is a quantitative expression of patchiness, determines the potential for the system to retain water, soil, and nutrients. The higher the ratio is, the lower is the ability to retain resources and the greater is the leakage from the system.

In arid shrublands, activities such as livestock grazing and firewood clear cutting are concentrated in the shrub patches, which leads to abuse of the shrubs by humans and their livestock (McIlvanie 1942; Hacker 1984, 1987). The overutilization of shrub production reduces the size and number of these patches. Reduction in shrub cover leads to an increase in crust cover. The change in the landscape mosaic causes desertification, that is, an increase in resource leakage, followed by reduction in production and diversity (Graetz 1991; Thomas 1995).

This shrubland desertification model suggests that ecosystem management aimed at increasing productivity and diversity of desertified shrublands should work toward reducing resource leakage.

Ecosystem Management of Desertified Shrubland

The ecosystems of the northern Negev desert have been used by humans for thousands of years. Humans have been using the ecosystem production mainly for livestock grazing, firewood, and construction. Uncontrolled use of the ecosystems has caused a reduction in shrub cover and caused soil erosion (Evenari and others 1983). This prolonged process of exploitation has resulted in increased crust cover and decreased shrub cover. The findings of our research indicate that under such conditions an increased leakage of resources and decreased production and biological diversity should be expected.

The Forestry Department of the Jewish National Fund (JNF) has decided to manage the desertified areas of the northern Negev in an attempt to convert them into recreational parks (Shachak and others 1997). Management objectives include reducing leakage of resources, thereby increasing productivity and diversity in desertified areas. The problem is, how can patch distribution and the flow of resources be changed?

A management solution for decreasing resource leakage is to create sink patches. Sink patches are characterized by two features. The first is a structure that prevents the flow of runoff water, soil, organic matter, and nutrients from a landscape unit. The second is a storage unit that maintains and absorbs water, organic matter, and nutrients. The resource-enriched man-made sink patches function similarly to the shrub patches destroyed during the desertification process. Historically, other methods have also been developed to collect leaking resources from deserts and desertified ecosystems (Kedar 1967; Evenari and others 1983; Bruins and others 1986; Yair and Shachak 1987).

In the ecological parks of the northern Negev, we use contour catchments and hill-slope minicatchments as management practices to create sink patches on the slopes. In the valleys, we use limans and streambed terraces. Limans are earthen dams across the streambed, with an access channel (spillway) on the side of the dam, which enables excess runoff water to flow downstream. Streambed terraces are stone constructions built across the streambeds to collect and store floodwater. Excess runoff flows over the stone dam downstream.

Ecosystem management principles were developed to guide the construction of man-made sink patches. The type of patches and the number, size, and location in the watersheds were dependent on ecosystem management principles, which were adopted to ensure sustainability of the system. Sustainability implies long-term function of the man-made sink structures, that is, persistence of the structures that prevent the leakage of resources and support the vegetation in the man-made enriched patches.

Since runoff water serves both as a principal resource and as a central vector for soil and nutrient transportation, the principles involve controlling water flux and are based on the properties of resource leakage in drylands. Leakage is in pulses (Noy-Meir 1973), and the frequency and magnitude of the leakage pulses is spatial scale dependent. On a slope scale, the magnitude of water leakage increases with the spatial scale (Figure 3). On a watershed scale, Evenari and colleagues (1983) found that the frequency of runoff generation in the valley is negatively related to watershed size whereas the magnitude is positively related to watershed size.

The first principle of ecosystem management adopted for desertified shrublands was to minimize resource leakage by constructing man-made sinks. This can be done by constructing a large number of contour catchments. The contour catchments are the most effective in preventing leakage, because they are located on the slope where the magnitude of runoff pulses is low. In addition, the amount of runoff can be controlled by adjusting the distances between the contour catchments. However, there are constraints on the number of contour catchments. Rocky slopes with shallow soil limit the space available for construction of contour catchments. In addition, a trade-off exists between the distribution of runoff to the slope and to the valley. Too many contour catchments limit the movement of water to the valley and reduce its productivity.

The second principle refers to the number of man-made sinks. Sink patches should be constructed such that they can collect and store, in just a few runoff pulses, sufficient water to support vegetation growth in the long dry periods between pulses. This principle can be implemented by adjusting the number of man-made sinks to the size of the area that leaks and the frequency and magnitude of runoff events.

The third principle refers to the size of the man-made sinks. The size of the sink patches should be adjusted to the water volumes needed by the vegetation in the enriched patches. As the demand for water increases, the patch size should increase. High water volume implies that the man-made sinks should be constructed to collect water during extreme runoff events, with high water discharge values. Man-made sinks may be severely damaged by high water discharge. Therefore, the longevity of the structure that prevents resource leakage decreases with increased sink size.

As part of an ecosystem management project aimed at establishing recreational parks in desertified shrublands in the Negev, the JNF is introducing man-made sinks to about 5000 ha, in an area with 150- to 250-mm average annual precipitation (Shachak and Pickett 1997). The management activities are concentrated mainly in open landscapes near urban and rural settlements. Most of the management efforts are in areas unsuitable for either agriculture or nature reserves. The basic approach to the management of these lands has been to add man-made sink patches enriched with runoff water and nutrients for planting trees and enhancing natural vegetation growth that may be used for grazing.

These management activities have increased the value of the land for the local population. These modified landscape systems, located near urban settlements, serve as green belts. Scenic roads, walking trails, and observation points in areas managed by the JNF project fulfill the needs of the nearby urban population for open landscape. They also serve as rangeland for shepherds.

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