SOLAR ENERGY CONVERSION: AN
ANALYSIS OF IMPACTS ON DESERT ECOSYSTEMS

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This progress report lays out in introductory fashion, based on a thorough literature review, some of the important potential ecological impacts that might occur when solar collector arrays are constructed and maintained in the desert Southwest. These impacts are categorized under major environmental consequences of solar collector development, that is, shading, wind deflection and site destruction and soil disturbance. Under these major categories secondary impacts are developed to show the significance of altering desert ecosystems with solar conversion systems. Some of the secondary impacts which include abiotic changes in radiation, temperature, heat flux, soil moisture and erosion, and biotic changes such as increased plant productivity and species diversity are discussed as to their short and long term significance in the desert system.

The report presents a brief description of the solar collector simulator array being constructed in the desert to test many of the concepts developed during the early part of Phase I of this project.
INTRODUCTION

The arid and semi-arid regions of the Southwest in the United States and northern Mexico lend themselves to being ideal locations for development of solar energy conversion systems. These areas are dry, have little cloud cover and maintain a low sparse vegetation cover that will not interfere with solar collecting devices.

Although the South and Southwest are having a population boom, they are areas that will continue to have large open, relatively unproductive areas, especially the desert regions. It is likely that large acreages of these so-called desert wastelands will be converted into solar farms when solar technology is more advanced.

Already some demonstration projects are operational, showing how large areas of collectors might be put to productive use. Two pilot solar irrigation projects are operating in New Mexico and Arizona. ERDA has established an irrigation project in Willard, New Mexico that permits irrigation pumping 24 hours, while Northwest Mutual and Battelle have developed a solar irrigation system near Gila Bend, Arizona that is used to recover shallow irrigation losses. Both of these systems are solar thermal distributive systems and cover only a small area of ground. The solar collector structures are, however, quite different from the surrounding terrain and thus alter micro-environment in the area.

ERDA has also funded the development of a test solar thermal tower using reflecting heliostats at Sandia Laboratory near Albuquerque, New Mexico. This point or centralized system concentrates reflected solar radiation at one point. The heliostats are arranged and operate to follow the sun and avoid excessive shading of each other. Each of these structures which may be as large as twenty feet square (6x6M) modify the microenvironment around and below them.
These demonstration and test solar collector facilities are undoubtedly just a beginning of an expanding energy production industry in the Southwest. These early facilities are small compared to the hundreds and perhaps thousands of acres eventually to be covered by solar collectors.

If long range plans predict coverage of extensive land areas by solar collectors, one can assume that large areas of the desert will be modified by construction and environmental changes due to structure location.

The desert ecosystem appears to be a stable system, however, although the Southwest has been dominated by desert or other semi-arid vegetation types for many centuries, many areas have been shown to have been modified within a short time period due to man's activities (Martin 1963, Hastings and Turner 1965). It is not unexpected then to assume that development of any extensive set of solar conversion units, whether they are solar thermal collectors or heliostats, will have an extensive modifying effect on the surrounding ecosystem.

Environmental modifications are of two types, short and long term. Short term or immediate changes in the microenvironment of a structure in the desert can be readily demonstrated by appropriate instrumentation. These are, however, only physical changes and might quickly be reversed if the modifying structures were removed. On the other hand, if these short term microenvironmental changes are permitted to continue for any length of time, they will then trigger, both directly and indirectly, longer term modifications of the ecosystem that are not so readily reversible.

Long term modifications are considered to be ecological changes because not only is the microenvironment altered but the biotic components of the ecosystem are also changed. Although ecological changes may take many years to occur, the ecosystem once stabilized under new conditions will remain changed unless man again alters the overriding controlling conditions.

Ecological changes resulting from construction and operation of solar collector systems are impossible to quantify without taking some actual measurements. It is possible to estimate changes in such factors as solar
input, energy budgets and soil moisture using equations based on hypothetical structures and environmental processes, but every ecosystem is variable and it is this variability that will cause hypotheses based on theoretical calculations to be in great error. Other ecological factors such as wind movement, soil erosion and biotic processes are impossible to predict. One can draw hypothetical conclusions based on the literature and the theoretical calculations of variations in physical processes, but this is only a preliminary step. From these early predictions one must design tests to prove or disprove established hypotheses.

This proposal (1) is designed to demonstrate how one must approach research into evaluating ecological impacts of solar energy conversion systems and (2) establishes and carries out the research design necessary to show these impacts.

PHASE I : PROGRESS

The original proposal that resulted in ERDA contract EC-77-5-02-4339 presented a logical sequence of research for demonstrating ecological consequences of solar conversion systems. This sequence was presented in three phases with Phase I being supported under the initial funding.

At this writing, Phase I (seven months) is just half completed. It will be impossible in presenting a proposal for continuation support to discuss all the expected results from Phase I but hypotheses and directions of research developed up to this point will be presented.

Phase I of what was originally presented as a three phase project was designed to gain ideas and develop hypotheses that could be tested over later, long term research phases. A thorough review of the literature has provided many ideas both as to possible ecological consequences of solar collector structures and about alternative ways to test for or demonstrate these ecological impacts. Phase I data will demonstrate that there are some environmental and biotic parameters that may be more sensitive to construction of solar collectors than others. These parameters are the ones that should be more closely studied in future research.
Phase I leads directly into Phase II for which this proposal is requesting funding. Phase II is designed to make initial as well as expanded ecological tests of solar collector structures. Phase II is expected to last considerably longer than Phase I, reflecting the necessity of looking at ecological processes as long term processes rather than short term or instantaneous consequences. Phase II should still be considered a baseline data collection phase but it is also a major expansion of actual data collection over Phase I. Phase II should give most of the basic answers needed to predict impacts of different solar collector systems on desert ecosystems. It is not designed, however, to test mitigating methods if the ecological consequences are too severe, or to turn ecological impacts into ecologically beneficial consequences which is a real possibility.

PHASE I : PROBLEM ASSESSMENT

Phase I was designed to assess the potential problems of desert ecosystems modification that might arise if solar conversion systems such as heliostats (thermal towers) or distributive solar thermal collectors were constructed over large areas in the arid Southwest. This assessment phase was approached in two fashions.

First, the literature was thoroughly searched for all relevant data or ideas that might help with analysis of solar conversion system impacts. This literature search was not limited to solar collectors or to the Southwest but reviewed all worldwide literature that might pertain to structures, either natural or artificial, and their influence on arid or semi-arid ecosystems. In addition, the basic and applied ecological literature as well as appropriate engineering literature were reviewed for conceptual matter that might be even peripherally considered pertinent to this study. Analyses and concepts developed from this literature search are discussed later in this section and will be developed in detail in the final report of Phase I.

Second, because solar conversion systems are only in the construction or planning stage and those that are under construction are not necessarily typical of future systems, structures simulating solar conversion panels are being constructed at a relatively barren desert site in Arizona. This site
is typical of those identified as good solar collector sites in Maricopa County, Arizona by Black and Veatch (1977).

These simulated solar panels are designed to rotate around a vertical axis and are individually large enough, 12x16 feet [(3.7 x 4.9 M)], to influence a large area of ground beneath and around them (See Figure 1 for detail). The panels are arranged to avoid shadowing each other at noon at the winter solstice. They are set at a 45° angle and are surfaced to reflect solar radiation thus simulating most solar conversion systems presently in the research and development stage. The simulator panels are clustered to permit measurement of interval effects within an array of solar collectors rather than testing for the impacts of one or two isolated units (Figure 2).

This array of panels will allow measurement of some short term micro-environmental data during Phase I but will also permit longer term studies on modification of desert ecosystem processes during the longer time spans of Phase II and other later phases of this research.

Theoretical Impacts

The literature review presented many differing views on the possible consequences of construction and maintenance of solar collector arrays in a desert ecosystem. Not all data agreed but by using the most reliable information, theoretical impacts of solar collectors were developed. The approach taken was to break the impacts down into major categories and subcategories and develop theories within each of these. The major categories are:

1. Shading
2. Wind Deflection
3. Physical Disturbance

Shading

Solar Radiation

Solar radiation, the environmental variable which is probably in least demand to living organisms in the southwestern deserts, will possibly be the most affected by arrays of solar collectors. How much of the incident solar radiation is intercepted by collectors, and thus redirected away from the
Figure 1a. One of 16 solar collector simulators which are placed in a square grid spaced 24 feet between vertical rotation posts.
Figure 1b. Solar collector simulators (12x16 ft) constructed in the desert near Phoenix. The right picture demonstrates how the panels can be rotated on a central axis.
Figure 2. Artist conception of the solar collector simulator array.
ground surface, will depend on the types of collectors used, and the spacing (or "packing factor") of the collectors along east-west and polar axes.

Black and Veatch (1977) analyzed a hypothetical photothermal collecting facility, and determined that an array of heliostats covering between 42% and 56% of the ground surface would intercept 59% and 78% of the annual daily direct radiation, respectively. Their calculations were made at the equinoxes, and thus did not account for changes in azimuth of the sun with season. They assumed that interception of diffuse radiation would be equal to ground coverage of the heliostats (i.e., 42-56%), although acknowledging that this is probably an underestimate because tracking mirrors should intercept a greater proportion of the more intense diffuse radiation from the sunward part of the sky than would a horizontal surface. Assuming total incident radiation in the desert Southwest to be 80% direct and 20% diffuse (Liu and Jordan 1960), between 55% and 73% of the total incident radiation will be intercepted by heliostats and removed from the desert ecosystem (based on Black and Veatch 1977). A reduction of such proportion is highly significant.

A more recent study of the "power tower" type of solar collection facilities indicates that only 25% of the ground area will be covered by heliostats (Hildebrandt and Vant-Hull 1977). The heliostat coverage will vary from 40% near the tower to approximately 10% near the periphery of the heliostat field, because with increasing distance from the tower greater amounts of blocking of reflected sunlight by adjacent heliostats occur. With reduced ground cover there will be less shading than the figures given by Black and Veatch (1977). The design suggested by Hildebrandt and Vant-Hull (1977) would probably result in removal of less than 50% of the total incident radiation from the system. Unfortunately, we were unable to obtain any values for ground coverage of projected photovoltaic arrays.

Photovoltaic arrays may suffer greater penalties from shading loss due to adjacent collectors, and thus should be installed at reduced packing factors compared to photothermal systems (Arizona State University, 1977). If so, solar radiation losses would be reduced in photovoltaic arrays but still should not be substantially below 50% of total incoming radiation.
Since solar arrays are designed to operate year round, packing factors should be designed to enable the solar facilities to produce sufficient quantities of energy in the winter, when shading losses from neighboring collectors will be most intense. Thus, during the growing season in late spring to early fall, the amount of intercepted radiation, and thus shading of the ground, would be expected to be less than estimated values due to the higher azimuth of the sun. On the other hand, shading of the ground surface in the winter months, also a very productive season in the Southwest desert ecosystems, could be nearly complete, especially during the morning and afternoon.

The types of solar collectors used will play an important role in how much of the ground surface is shaded, and how that varies on a temporal basis. For instance, heliostats (designed by Martin Marietta) being tested at the Sandia Laboratories, Albuquerque solar thermal test site have spacing between the mirrors while others to be tested may be solid. This difference in reflectors may not cause significant differences in absolute incident radiation reaching the ground surface, but could be important with regard to duration of shading of a given area of ground, as sun spots will move across the desert floor as the system tracks the sun.

Different types of proposed photovoltaic collectors will produce different seasonal patterns of shading of the ground surface (Arizona State University 1977). Collectors which rotate on a single horizontal axis will produce almost complete shading of the ground surface within the collector array in the winter (with collectors rotating on a polar axis) or on a diurnal basis (early morning and late afternoon for east-west axis rotation of collectors). Conversely, a collector tilted at 45° from the zenith and rotating around a vertical axis to track the azimuth of the sun (similar to the simulators constructed in Phase I) will not exhibit significantly different seasonal shading (Arizona State University 1977). Collectors rotating on vertical and horizontal axes simultaneously exhibit the smallest shading losses, and thus can be placed at the highest packing factors. Thus, it is evident that knowledge of specifics involved with collector design is a necessary pre-requisite in order to predict interception of incident radiation, and thus energy loss from the ecological system.
Solar collectors will also affect the thermal (long-wave) radiation emitted by the ground to the sky. In a normal open desert system, intense heating of the ground surface during the day is followed by a high rate of reradiation at night from the ground to the "cold" sky (Sellers 1965), thus resulting in rapid cooling of the ground surface. If 10 to 40% or more of the sky is blocked by solar collectors, then approximately the same percentage of long-wave reradiation would be intercepted. If the collectors are in a stow (inverted) position at night (Hildebrandt and Vant-Hull 1977), then the thermal radiation intercepted will be redirected back toward the ground.

Therefore, solar collector arrays will substantially decrease incoming solar radiation in the daytime, as well as reduce outgoing thermal radiation in both the day and night. The result will be reduced net radiation under the collectors on a daily basis, and a substantial reduction in average hourly radiation flux. Several related studies support these predictions.

Bajza et al. (1977) found an irrigated landscape (i.e., with trees and large bushes) to have lower incoming radiation at the ground surface than a desert landscape during the day, as well as having lower long-wave emitted radiation at night due to less sky exposure (as well as cooler surface and subsurface temperatures). Net radiation on the irrigated landscape never fell below zero, while on the desert landscape it was very high during the day, and fell well below zero at night.

Results by Lowe and Hinds (1971) are similar. They found a palo verde tree in winter in the Arizona desert to reduce incoming radiation by 50% compared to the open, while also reducing effective outgoing radiation at night by the same amount. The result was a maximum diurnal net radiation flux under the tree of just 44% of that observed in the open. Patten (1975) found similar reductions of incident radiation by palo verde trees in the Sonoran Desert near Phoenix.

Of potential importance is the amount of radiation a given area of ground will receive as bands of sun and shadow move across the desert surface. When an area is in shadow (i.e., shielded from direct beam radiation), the area will still be receiving diffuse radiation. How much will depend upon
elevation of the sun. As the sun increases in elevation, the amount of diffuse radiation received in shade spots should increase. A given area of ground in a patch of sun may also receive greater amounts of solar radiation than it would in the open desert. For example, Rosenberg (1974) found areas near a tree shelterbelt to receive amounts of daily radiation equal to an area remote from the shelterbelt. Although shaded for several hours in the morning, the site near the shelterbelt received additional reflected energy off the shelterbelt in the late afternoon. Furthermore, Patten and Smith (1975) note that solar radiation can be extremely high (approaching the solar constant) when scattered cumulus clouds provide large amounts of diffuse radiation in addition to direct radiation. Such a phenomenon will probably occur due to reflection off nearby collectors, and could have significant ecological effects. Although solar radiation under collectors will be greatly reduced on a daily basis, it may be intense at certain times of the day.

Temperature

Daytime air temperatures under heliostat fields and photothermal and photovoltaic arrays will probably be only slightly lower or not significantly different than in the open desert. Air temperatures in shaded microhabitats are generally slightly cooler during the day (Patten and Smith 1973; Hanson and Ravzi 1977, Bajza et al. 1977), with the differences being more pronounced in the dry season (Patten and Smith 1974). Daytime air temperatures near the ground surface should be substantially cooler under solar collection arrays (Black and Veatch 1977); this has also been observed under large Sonoran Desert shrubs (Patten and Smith 1974). Also of potential importance in collector fields is the observation of Tuller (1973) that areas shaded from morning sun have a higher mean daily temperature than areas shaded from afternoon sun.

Night temperatures in areas shaded during the day are not as well documented. Bajza et al. (1977) observed nocturnal air temperature to be higher in a shaded microhabitat, evidently because the tree canopies which produced the shade also reduced the amount of escaping long-wave radiation at night.
Patten (1975) obtained similar results for microenvironments beneath palo verde trees. Nighttime temperatures under collector fields may not be as easy to predict due to the complication of wind deflection by individual collectors, and their effect on nocturnal inversions, which will be discussed later. Although early evening temperatures should be cooler under collectors (assuming cooler temperatures during the day), interception and possible re-radiation of long-wave emitted radiation should retard nocturnal cooling relative to that in the open desert. ERDA (1977b) predicts no significant difference in nighttime temperatures.

When comparing temperature and organism function, Terjung et al. (1970) state that total environmental radiant temperature is more important in determining organism heat gain or loss than the popularly used air temperature. Although variously calculated as the sum of bare soil and sky temperatures (Terjung et al. 1970), or calculated from the total radiation flux using the Stefan-Boltzmann equation (Schmidt-Nielson et al. 1965), studies using this parameter have shown significant reductions in radiant temperatures in shaded desert habitats. Dawson and Denny (1969) report all-wave maximum temperatures beneath the canopies of black oak and mulga (*Acacia*) trees in arid Australia to be 55% and 49% of that in the open, respectively. Lowe and Hinds (1971) found palo verde trees in Arizona to reduce this parameter an average of 37% in the winter with respect to daily maximum value. Furthermore, Lowe and Hinds (1971) found winter nocturnal radiation temperatures associated with the infra-red flux to be much higher under a palo verde canopy than in the open, once again due to the canopy blocking the sky and thus limiting loss of thermal radiation from the surface.

Surface and soil temperatures should be influenced far more than air temperatures due to shading. Cloudsley-Thompson (1965) and Patten and Smith (1974) observed desert surface temperatures in the shade to be similar to air temperatures, while exposed temperatures may reach 80°C (Cloudsley-Thompson 1965), with a diurnal range of up to 55°C (Geiger 1965). Although trees and shrubs in arid regions are known to significantly reduce surface temperature in the warm season when they are fully leafed out (Shreve 1931,
Hinds 1967, Hinds and Rickard 1968, Patten 1975, Bajza et al. 1977), Lowe and Hinds (1971) have also shown reductions of up to 13°C in the winter from shading of deciduous desert trees.

Soil temperatures are reduced in shaded areas during the day (Shreve 1931, Hinds and Rickard 1968, Patten 1975), and possibly at night as well due to the time lag of soil temperature fluxes in relation to air and surface temperature (Shreve 1931, Hadley 1970). Further supporting the concept of reduced soil temperatures in the shade is a study by Abd El Rahman and Batanouny (1966) who found soil temperatures in an arid watershed to be more highly correlated with incoming radiation than with air temperature. A further ameliorating effect of shading is the fact that shaded areas tend to have less diurnal (and possibly seasonal) variation than do exposed areas (Patten and Smith 1974, Bajza et al. 1977).

In conclusion, of the four temperature variables discussed (air temperature, radiant temperature, surface temperature, and soil temperature), air temperature is the only variable which should not be substantially reduced due to shading by solar collector arrays, based on studies of natural desert systems. Interestingly, air temperature is probably the temperature variable of least importance with regard to physiology, behavior, and distribution of desert organisms. Also, shading of the desert surface has a more significant influence on diurnal variability of environmental temperatures than on absolute or mean values, further indicating the ameliorating effect of shading on temperature.

Soil Moisture

Studies in arid and semi-arid regions generally indicate shading by vegetation to cause a decrease in evaporation rate and thus increase soil moisture relative to open areas (Shreve 1931, Abd El Rahman and Batanouny 1965, 1966, Bajza et al. 1977). Although Shreve (1931) found evaporation rates in the open and in the shade of a palo verde tree to be similar in all months of the year, he did observe the shaded microhabitat to exhibit higher soil moisture content following heavy summer rains as well as following light rains in the cooler months of the year.
With the exception of Shreve (1931), evaporation studies indicate shading significantly reduces water loss from arid soils. Hellwig (1973) concluded that solar radiation input far outweighs air temperature and relative humidity as a factor affecting evaporation from arid sandy soils, while Krishnan and Thanvi (1972) found the number of hours of daylight to be an important variable in predicting evaporation. Transpiration studies further support the role of radiation in water loss, as Abd El Rahman and Batanouny (1965) found shaded vegetation to exhibit less water loss per gram of tissue than plants in the open when both populations were well watered.

With respect to arrays of solar collectors, Black and Veatch (1977) and Sears et al. (1977) predict that soil moisture under the array fields will be significantly higher than in the adjacent open desert. Furthermore, additional water may be available between the collectors for short periods following rain storms due to precipitation runoff (Meinel and Meinel 1972) and possibly due to water used to clean the heliostats (Black and Veatch 1977) or photovoltaic collectors (Sears et al. 1977) The amount of inter-space soil moisture compared to that under the collectors is unknown and should be determined. In conclusion, removal of a majority of the incident solar radiation from an arid ecosystem should tend to prolong favorable moisture conditions, and reciprocally shorten the duration of adverse (i.e. drought) conditions.

Plant and Animal Responses

The desert Southwest is considered a harsh environment for plant and animal life in which the major limiting factor is moisture. Most of the growing season is characterized by low soil moisture and high evaporitivity (Noy-Meir 1973). If shading by solar collectors, through interception of a large proportion of incoming solar radiation, increases soil moisture due to suppression of evaporation rate, profound changes could possibly occur on the desert floor underneath the collector arrays.

In the open, water-limited desert, plants generally have adaptations which increase the efficiency of water use. Morphological adaptations such
as hairy leaves, which increases albedo of the leaf (Billings and Morris 1951), are the product of evolution and may not be expected to be plastic in response to environmental changes. However, physiological adaptations also occur, such as the "behavioral" adaptation in which desert shrubs use stomatal control so that metabolic activities (related to open stomates) occur mostly, or exclusively, in times of low evaporitivity (Caldwell et al. 1972, Evenari et al. 1972, Kappen et al. 1972, Syvertsen et al. 1975), such as the early morning. In this situation, radiation input could possibly be a limiting factor to primary production (Noy-Meir 1973). If soil moisture conditions were substantially improved under a collector array, and stomatal rhythms were indeed a plastic response, then stomatal opening could occur at more optimal times (i.e., when solar radiation was at maximum levels). With overall reduced solar radiation input in collector arrays, and occasional periods of high radiation input between collectors, stomatal rhythms appear important.

Meinel and Meinel (1972) feel that increased moisture conservation under collector arrays may improve the ability of an arid land to support growth of grasses of commercial importance to ranchers. These grasses, perennial bunch grasses, are well known to respond only to adequate soil moisture levels in the warm summer months (Schreiber and Sutter 1972, Mott 1973, Cable 1975). At the present, perennial grasses are scarce or non-existent in areas earmarked for large solar collection facilities. Thus, without major seeding efforts, it appears that many years of significantly increased soil moisture in the summer would be required for such a change to take place.

If a change in vegetation occurs due to shading, the most immediate vegetation response will be an increase in ephemeral forbs and grasses. Desert annuals are well known to respond to pulses of biomass after significant inputs of precipitation (Went 1949, Noy-Meir 1973, Beatley 1974b, Slade et al. 1975). Furthermore, their tendency to accumulate underneath shrubs (Shreve 1931, Muller 1953, Patten 1975) indicates a certain degree of tolerance to shading or perhaps a requirement for shading. Even in a wet season, Patten (1975)
observed annual productivity to be greater under shrubs, although increased nutrients under shrubs could be implicated in such a case (Muller 1953). According to Shreve (1931), shading is important for success of herbaceous plants in arid areas due to the more favorable conditions provided during the very critical rainless periods in their early history.

Accurate prediction of possible successional changes in plant populations due to decreased solar radiation and increased soil moisture is difficult to assess, especially considering the significant abiotic modifications possible in collector arrays. Many desert plants have precisely evolved germination requirements (e.g., McMillan 1970, 1973) and phenological dynamics (e.g., Davies 1976) dependent upon moisture, photoperiodic, or thermoperiodic signals. Drastic, long term changes in these cues could make the plants which have adapted to the open desert situation not as adaptive, potentially resulting in a relative increase of secondary species with more plastic responses, or invasion of "opportunist" species such as weeds.

Change in animal populations will, to a large degree, depend on vegetation changes as well as man's activities. An increase in forbs and grasses will result in an increase in rodents, as rodent reproduction is known to be tightly coupled to annual production in the Southwestern deserts (Reynolds 1958, Beatley 1969, 1976, Soholt 1973, Van De Graaff and Badida 1973). High production of annuals could then result in large numbers of rodents near the collector site. Relative proportions of heteromyid rodents and lagomorphs on the sites could depend on the relative success of forbs versus grasses.

Amelioration of the radiation balance by collector arrays on a diurnal and seasonal basis may make the areas under collectors a desirable habitat for surface animals. Dawson and Denny (1969) correlated movements of kangaroos in Australia to reduction in radiant temperature by small trees, as previously discussed. Animals of the immediate area around a collector field could seek the shade of collectors during bright, cloudless days in the summer months. This assumes a lack of constant maintenance activity by man. The collectors could also provide a warmer environment on cold winter nights due to a decrease in thermal long-wave radiation from the soil, resulting in
a less negative, and possibly even a positive nighttime radiant temperature (Lowe and Hinds 1971).

Shading, due to its effects on radiation input, thermal flux, and soil moisture, could have profound effects on the biota of the southwestern desert ecosystems in which large-scale solar collector arrays are placed. If soil moisture is indeed significantly increased (or at least droughts decreased) the desert literature indicates the possibility of significantly greater plant production, potentially of an economically beneficial nature. However, prediction of change in altered systems with a history of disturbance will be difficult, as short term changes are not necessarily indicative of site potential.

Although not directly related to shading, an increase in man's activities at a solar collector site could cause dispersal of many of the existing animal populations; however, historically it has been shown populations of some mammal species such as rats and coyotes increase as a result of man's activities. Reptile species with small territorial ranges may increase in population because of the ameliorated environment created by the solar collectors.

WIND DEFLECTION

Velocity and Turbulence

It is generally assumed that arrays of solar collectors will decrease local wind speeds in both heliostat fields (Black and Veatch 1977, ERDA 1977b) and in photovoltaic or distributive photothermal arrays (ERDA 1977a, Sears et al. 1977). Wind flowing across a field of collectors will probably be forced upwards if striking the reflective surface of the collectors or downwards if striking the backside so that, although wind velocities may be greater than normal above the field, if the wind is from the South, they will be reduced below the array of collectors, although wind from the backside may also cause turbulence below the collectors. This area below the collectors is the area of importance when discussing ecological impacts of solar arrays in the desert.

Wind velocity in the southwestern deserts is more intense than most other areas of the continent. High wind velocity makes a region more arid
by increasing evaporation rate and desiccates plants. Thus, windbreak systems have been found to be useful in arid regions as a means of limiting the process of desertification (Van Eimern et al. 1964, Petrov 1966, Stepanov 1971).

Although windbreaks are designed and function to decrease wind velocity (Van Eimern et al. 1964, Rosenberg 1974), changes in turbulence due to windbreaks are not as easy to control or predict. Many studies have indicated turbulence to be reduced in the lee of wind shelters (Brown and Rosenberg 1971, Miller et al. 1973, Tuller 1973, Rosenberg 1974), while other studies have observed, despite a decrease in velocity, an increase in turbulence (Rosenberg 1966a, Van Hylekama 1970, Hanson and Ravzi 1977).

Rosenberg (1966a) observed turbulence to vary diurnally being more unstable in sheltered areas during the day, but more stable at night. Also indicating diurnal variation, Bajza et al. (1977) found an irrigated landscape with irregularly spaced wind obstructions to have many more hours of calm than an open desert landscape, but also exhibiting higher maximum velocities and turbulence due to funneling of winds during periods of peak wind speed.

Prediction of changes in wind speed and turbulence will thus be an extremely complex problem, and is further compounded by the various heliostat configurations proposed for use in solar thermal plants (ERDA 1976). Heliostats proposed by Honeywell and Martin Marietta consist of rectangular flat plates with gaps between the plates, while Boeing and McDonnel Douglas propose circular concave heliostats, with Boeing's enclosed in a plastic bubble.

Small gaps in heliostats may reduce wind velocity under the heliostats, as porous windbreaks are generally more effective than nonporous due to the fact that air which passes through the gaps can prevent the turbulent return of air which has overtopped the windbreak (Miller et al. 1975). However, if the gaps are too large (e.g., Honeywell heliostat configuration, ERDA 1976), jetting effects may occur and increase turbulence (Rosenberg 1974).

Rows of photovoltaic collectors should reduce velocity and turbulence, although our discussions with ERDA technicians and observations at the
Willard, New Mexico solar irrigation site indicated that trough-shaped solar thermal collectors arranged in rows may have increased turbulence and wind erosion compared to adjacent open areas during periods of high wind velocity.

Temperature and Heat Flux

The effect of wind deflection by solar collectors on temperature may be an increase in daytime air and soil temperatures, based on shelter studies of sites leeward of windbreaks (Jensen 1954, Aslyng 1958, Rosenberg 1966a, King 1970, Hanson and Ravzi 1977). Warmer temperatures due to wind deflection are assumed to be the norm due to a decrease in turbulent exchange resulting in more intense vertical temperature gradients (Rosenberg 1974). An exception is the findings of Stepanov (1971), who found that shelterbelts reduce surface temperatures of sandy desert soils.

Night temperatures apparently are not as consistently affected as daytime temperatures. Although there are studies which have observed warmer night temperatures in sheltered areas (Rosenberg 1966a, Tuller, 1973), Rosenberg (1974) concludes in a review of shelter studies that night temperatures will be lower in shelter due to more intense nocturnal air inversions. Since these inversions are common in the southwestern deserts, reduction of nocturnal air temperature due to wind deflection could be substantial.

Predictions of temperature changes under solar collectors tend to agree with the shelter studies in predicting increased daytime air temperatures under heliostats (Black and Veatch 1977) and photovoltaic arrays (ERDA 1977a). However, soil temperatures are predicted to be unaffected (Black and Veatch 1977), and nocturnal temperature will either be unaffected (ERDA 1977b) or slightly warmer (Black and Veatch 1977). Assumed decreases in turbulence will be a factor here, as various configurations of collectors and arrays of collectors will influence degree of turbulent exchange within the array field.

Regardless of whether temperatures will be warmer or cooler, the absolute changes of temperature in collector fields should be slight due to wind deflection. If, however, daytime temperatures are warmer and nighttime temp-
eratures cooler, then wind deflection would have a greater effect on rates of heat flux than on temperature per se.

Soil Moisture and Humidity

Wind speed has a major influence on evaporation rate (Penman 1948, Hellwig 1973), especially in arid regions (Krishnan and Kushwaha 1973). Quantitatively, Van Eimern et al. (1964) found evaporation from flat moist containers to be proportional to the square root of the wind speed. Thus, a decrease in wind speed and turbulence should result in reduced evaporation rates, and concomitant increases in soil moisture. This has been observed experimentally in numerous shelter-type studies (Jensen 1954, Van Eimern et al. 1964, Marshall 1974, Rosenberg 1974).

Reduction of evaporation by wind deflection in arid regions may be proportionally greater than the reduction of wind velocity. This is because a major beneficial aspect of wind deflection with respect to moisture conservation is the reduction of the advection of sensible heat from surrounding unsheltered areas (Miller et al. 1974). This is probably an important reason why planting of shelterbelts with the resultant wind reduction is considered more effective in arid and semi-arid regions (Siddoway 1969, Rosenberg 1974), and in regions with continental climates (Van Eimern et al. 1964, Marshall 1967).

The relevance of these studies to the microclimate of heliostat and collector fields is apparent. If soil moisture is higher under collectors than in the surrounding desert, then significant reductions in wind speed by the collectors could significantly reduce advective losses of moisture to the surrounding drier desert.

With increases in soil moisture will be increases in humidity and vapor pressure of the air under the collectors, as has been observed experimentally in almost all shelter studies (Rosenberg 1974). Increase in these variables, together with soil moisture increase, should result in a much more mesic microclimate relative to the open desert.
Plant and Animal Response

The effect of a more mesic environment in an arid region should be a significant increase in photosynthetic rate, and thus primary production. Because of reduced evaporative demand during periods of greatest water stress, and increases in water vapor pressure, plants should respond by maintaining greater stomatal aperture for longer periods of time than would be possible in the open desert.

Increases of stomatal aperture in sheltered crops are well documented (Rosenberg 1966a, Brown and Rosenberg 1971, Miller et al. 1973, 1974), as well as increases in water use efficiency (Rosenberg 1966a,b, Rosenberg et al. 1967, Miller et al. 1973). A combination of increased water use efficiency and increased soil moisture could result in substantial increases in primary production. Furthermore, nocturnal respiration rates may be lower in sheltered areas due to cooler leaf temperatures (Miller et al. 1973, Rosenberg 1974). A combination of cooler nighttime temperatures and increased daytime transpiration rate (and thus increased latent heat loss) would result in the cooler leaf temperatures.

It has been suggested that, at low wind speeds, the photosynthetic rate in a sheltered field may be decreased because of a shortage of carbon dioxide in the air surrounding the leaves (Lemon 1970). In a thorough study of this, Brown and Rosenberg (1972) concluded that if decreases occurred they would be slight, and may limit photosynthesis only in dense crop canopies. In the desert, with its sparse vegetation, carbon dioxide is not considered a limiting factor to plant production.

In conclusion, the influence on plant growth of reduced soil and atmospheric moisture stress, possible higher soil temperatures, reduced mechanical motion and lower vapor pressure deficit should be beneficial in the water stressed desert habitat.

The response of animal populations to a more mesic environment with less advective water loss potential should increase the desirability of the habitat, especially in warm, dry seasons. Increases in plant production will also be conducive to increase in animal population numbers, as has been previously discussed.
Physical Disturbance

Future construction of solar collection "farms" on large tracts of desert land will have an impact on the environment of the construction site. These impacts will range from minor trampling by maintenance personnel to complete surface clearing of areas in the vicinity of structural supports of individual collectors. The total amount of disturbance in both construction and maintenance phases will have important consequences with respect to the ecological potential of the desert beneath the collector fields, and is suggested to be of significantly greater importance than the shading and wind deflection effects imposed by the collector arrays, at least in proposed photovoltaic systems (Sears et al. 1977).

The desert ecosystem has reached its relatively stable but delicate balance over a long period of time. The desert ecological literature presents ample evidence that where man has concentrated his activities in the desert, the desert ecosystem is drastically altered and, even though the activities may be discontinued, recovery may take many decades or centuries before the desert ecosystem again reaches a state of dynamic equilibrium. Some of these studies can be applied to the current problem of what changes may occur in soil structure, moisture regime, surface characteristics, and biota when large solar conversion units are placed and operated in the desert.

Soil Structure

Several parameters have been utilized experimentally by researchers to assess the effects of compaction on soil structure. Bulk density, macropore space, diffusivity, and penetration resistance are parameters which indicate changes in soil structure. Knowledge of changes in soil structure is important, due to its effects on water availability, root growth, and aeration of the soil.

There are numerous studies indicating that walkers (Bates 1935, Chappel et al. 1971, Liddle and Greig-Smith 1975) and off-road vehicles (Davidson and Fox 1974, Webb 1976, Wilshire and Nakata 1976) have caused substantial increases in bulk density and penetration resistance, and
decreases in macropore space. Liddle and Moore (1974) found walkers and vehicles to reduce diffusivity in wet soils, but not in dry soils.

Studies attempting to examine reversibility of compaction generally indicate that short term, even intense, compaction is reversible. Long term compaction tends to cause more serious changes in soil structure, especially in deeper soil layers (Liddle and Greig-Smith 1975), often resulting in a site which does not readily recover to its pre-disturbance condition. In the desert, vehicles tend to primarily disturb the surface, which still takes as much as a decade to repair (Vollmer et al 1976, Webb 1976). Studies of off-road vehicle effects on structure of deeper soils indicate possible serious changes, effects of which may not become expressed ecologically until years after the original impact (Vollmer et al. 1976, Wilshire and Nakata 1976).

Studies of a wide variety of soils indicates that compaction has more serious structural changes in wet soils than in dry soils (Bates 1935, Parker and Jenny 1945, Martinion and Olmstead 1949, Jamison et al. 1950). Scheduling periods of heavy maintenance pressure during predictable dry periods could possibly reduce the potential for soil compaction.

In order to limit the amount of long-term compaction occurring after construction, vehicles should be excluded from as many areas as possible, being confined to specific roads in the collector fields. Vehicles have been found to significantly increase penetration resistance more than bulk density in sand (Liddle and Greig-Smith 1975). Increases in penetration resistance would decrease infiltration rate, and could inhibit penetration of the root systems of ephemeral plants. Deeper levels of soil would also be compacted by vehicles as opposed to limited compaction due to occasional trampling. Introduction of grazing is not recommended after a period of intensive construction-type surface disturbance, as soil recovery may be retarded (Lowe 1955).

Runoff and Erosion

In the southwestern deserts, a list of Candidate Sites for photothermal solar conversion units (Black and Veatch 1977) indicates topography to be an
important consideration in site selection. A vast majority of Candidate Sites are on plains with low mountains. They are typically located in lowland valleys or plains bordering more rugged terrain (Black and Veatch 1977). Thus many Candidate Sites will probably be gently sloping bajadas (alluvial fans), characterized by a desert "pavement" surface, a dendritic pattern of small ephemeral washes, and moderate to widely spaced desert scrub vegetation.

Shreve (1934) outlines factors which determine amount of runoff, the most important being: (1) intensity of rainfall, (2) degree of slope, (3) texture of the soil, (4) nature and density of the vegetation, (5) amount of litter or stones on the surface, and (6) moisture of the soil surface. Due to a combination of infrequent, high intensity rainfall events, presence of sparse perennial vegetation, and presence of a desert pavement surface, desert bajadas tend to have high runoff rates compared to other geomorphic surfaces, and moister regions (Shreve 1934). High runoff in the desert is also accompanied by increased erosion rates.

Some of the above factors will be influenced by soil compaction and above-ground destruction. Compaction, by increasing bulk density of the soil, will have an inhibitory effect on infiltration rate similar to that caused by a change in soil texture. Infiltration rate is known to increase with particle size increase (Fireman 1944), especially in arid regions (Evenari et al. 1971).

If substantial areas of the desert are cleared and graded, runoff will greatly increase. A cover of dead and/or living vegetation usually increases infiltration in arid zones (Tadmor and Shanan 1969) by reducing rain impact or through some physical or chemical modification of the soil surface (Lyford and Qashu 1969). To minimize erosion of the soils beneath collector fields, as much area as possible should be left undisturbed.

An important consideration when discussing erosion of desert areas is the common occurrence of a desert pavement surface. A desert pavement tends to form on desert bajadas due to loss of finer soil particles in runoff water, resulting in a stony cemented surface layer. Although it
tends to stimulate runoff due to its low infiltration rate, desert pavement surfaces protect the soft, friable soil underneath from erosion by wind and water (Davidson and Fox 1974). If disturbed, the protection afforded the desert pavement is for all practical purposes destroyed due to its slow rate of formation. Destruction and continued disturbance of desert pavement surfaces from construction activities and vehicles could thus lead to subsequent high erosion rates.

These factors, together with deep, irreversible structure changes from compaction, illustrate the desirability of using areas with little or no slope and coarse textured soils for future large solar conversion units.

**Soil Moisture**

Infiltration of water into the soil is inversely related to the runoff. Compaction and above-ground destruction of vegetation will tend to cause a decrease in infiltration rate, and thus decrease soil moisture. A possible exception would be that destruction of desert pavement could result in higher infiltration rates.

In addition to runoff changes, compaction will alter soil water conditions dependent on soil structural changes. Increases in bulk density of disturbed soils, with the resulting decrease in macropore space, probably decreases the amount of water that the soil can hold and the rate at which water can flow through the soil (Davidson and Fox 1974). The importance of texture in examining compaction effects is important due to its effect on soil moisture conditions. In fine textured soils, compaction results in a lower soil water potential and increased field capacity (Lutz 1945, Singh and Singh 1971). Effects of compaction on coarser textured soils are not as pronounced, with moderate compaction even improving water availability in some soils (Hill and Sumner 1967, Liddle and Greig-Smith 1975). However, severe compaction, which is readily achieved in sandy loams (Hill and Sumner 1967) will result in a decrease in moisture content at constant matric suction.

Although the possibility exists for short-term soil moisture increases in areas of disrupted desert pavement, serious compaction and above-ground
destruction will result in decreased levels of soil moisture. If soil compaction and surface disruption is not severe, significant changes in soil moisture may not occur due to construction and maintenance activities.

Temperature and Heat Flux

Few of the recent studies on impacts of walkers and off-road vehicles have examined potential changes in thermal conductivity of compacted soils, and thus the effects of compaction on overall heat flux in the desert ecosystem. Liddle and Moore (1974) found compaction of sand to increase its thermal capacity, as would be expected as density was increased. Conductivity was increased in dry soils, but was decreased in wet. The result was an increase in diurnal soil and air temperature ranges, which Liddle and Moore (1974) attributed more to vegetation removal than to compaction. In any case, significant above-ground destruction of desert habitat would appear to increase heat flux rates in the soil-atmosphere system throughout the day.

Black and Veatch (1977) discuss possible changes in the temperature regime of a desert system due to installation of heliostat fields. Several alterations are hypothesized as follows:

1. Compaction caused by heliostat field installation and maintenance would increase surface emissivity, which would result in decreased daytime heating of the air by sensible heat.
2. Compaction will increase ground surface reflectivity, resulting in decreased soil heating.
3. Compaction will increase ground conductive capacity resulting in decreased net radiation.
4. Compaction will decrease dry density, thus decreasing ground thermal capacity and thus soil heating.

All four of these modifications will result in a decrease in the daytime heating of the air. This, together with shading and soil moisture changes, should result in significantly cooler air and soil temperatures under the heliostat field.

Plant and Animal Response

Plant and animal response to construction and maintenance disturbance
will be two-fold, namely the response of biota to soil compaction and the
abiotic changes it causes, and to actual destruction of individual organisms
or populations of organisms. In the case of mobile animals, populations may
not be destroyed, but destruction of habitat could result in removal of
organisms via migration from within collector fields. Return of these organ-
isms would thus be dependent on the degree of restoration of the habitat.

Compaction has been observed to inhibit growth of herbaceous plants by
decreasing germination or inhibiting root growth (Kubota and Williams 1967,
Davidson and Fox 1974). In very sandy soils, compaction has been found to
be beneficial to plants (Liddle and Greig-Smith 1975). Unless serious com-
paction occurs on clayey or loamy sites, it should not be a major limiting
factor on ephemeral populations.

Soil texture and pore volume are recognized as very important variables
in determining distribution of shrubs in arid regions (Noy-Meir 1973). Although
comparative water relations undoubtedly plays a major role, several studies
have indicated aeration of roots as a reason for many shrubs with fibrous,
near-surface root systems occurring exclusively on sandy soils (Cannon 1915).
Several common types of plants requiring high levels of soil aeration are
creosote bush (Lunt et al. 1973), and some of the cacti (Cannon and Free
1917). Several studies have noted decreases in oxygen content of soils due
to compaction (Lutz 1945, Liddle and Greig-Smith 1975) but as yet, apparently
no similar results are available for disturbed desert systems. Even so,
succession of perennial vegetation in the desert due to compaction effects
appears unlikely.

Complete above-ground destruction of desert sites is eventually
followed by new populations of plants. The important question is what type
of plants succeed on the site relative to what existed there before. Some
studies indicate plant succession to be essentially lacking in desert vege-
tation (Muller 1940, Shreve 1951), i.e., if a creosote bush community is
destroyed, then creosote bush will return. Indeed, desert studies have
shown this (Wright 1970, Beatley 1974a, Mirpagel and Zembel 1976). Con-
versely, other desert studies have indicated distinct invader species to
occur (Wells 1961, Vasek et al. 1975a,b). These invader species are usually perennial forbs or subshrubs which were only secondary constituents of the previous undisturbed communities.

If invader species do occur, then regeneration of long-lived dominant perennials may be expected to return after clearing in a sigmoid fashion, i.e., slow initial regeneration followed by rapid intermediate development as the invader species begin to be outcompeted (Vasek et al. 1975b). This can be a time consuming process, as evidenced by clearing effects still being noticeable in a heavily disturbed desert area 33 years after the disturbance took place.

If seeding of perennial grasses is attempted in order to take economic advantage of the moderate microclimate under collector arrays, and in an attempt to discourage weed growth, then several considerations may be important. Desert grassland species are often soil texture specific (Herbel et al. 1973), and seeding is often not successful on highly erosive sites or ones which form a hard surface crust (i.e., desert pavement). Establishment of rangeland grasses is also generally unsuccessful on sandy soils of arid regions due to windblast destruction of seedlings (Fryrear et al., 1973), although the shelter effect imposed by the solar collectors may give mechanical protection to seedlings from sand blast (Rosenberg 1974).

In general, the desert literature indicates that succession is a variable and often unpredictable phenomenon. This variability also tends to increase with disturbance; thus complete destruction of above-ground communities would be the hardest to predict with regard to revegetation. A further generality is that rate of revegetation from complete clearing is inversely related with the degree of aridity in a disturbed area, meaning that areas of higher relative production and diversity will revegetate more quickly. Thus, although significant areas may be cleared in the construction phase of these solar projects, the more mesic environment provided by shading and wind deflection should aid revegetation of the sites relative to disturbance in the open desert.

Succession of plant communities will have a profound impact on animal
population dynamics. Reproduction in desert animals has been documented to be highly correlated to abundance of food sources, as previously discussed. If food sources are available, animal populations which were formerly removed from sites due to intensive construction activities would be expected to return due to moderated microclimatic conditions under the collectors. These animal numbers could be significantly greater than what was originally there, assuming greater plant production and thus standing biomass. Such potential system imbalances (ERDA 1977a) would probably not be ecologically destructive, and may be of value in regulating standing vegetation biomass, which could become a problem to normal heliostat or collector operation and maintenance. Exclusion of animal migration by fences would result in an increased standing crop of weeds, possibly requiring application of herbicides over large tracts of desert land.

Expected Data from Simulators

The field data needed to begin to substantiate the concepts put forward based on the literature search and the ecological background of the investigators were only just beginning to be gathered when this continuation proposal was written. Actual microenvironmental data gathered at the solar collector simulator site and possibly at other types of shelters in the desert will be presented in the final report of Phase I. Limited data of biological changes due to shading and/or sheltering in the desert will also be presented.

We do not believe that there are any structures similar enough to solar collectors, in terms of construction and peripheral activities, to permit the gathering of accurate biological data comparable to that one might obtain around solar collectors. Therefore, any biological data we do obtain from around other shelter or shading structures will only suggest what might be taking place in ecosystem process changes around solar collector systems.

The data we anticipate to report later, although limited, will include (1) temperature profiles (air and soil) at various locations around and under the collectors, (2) variations in air movement as influenced by the collectors at different heights above the ground, (3) variations in solar
radiation including net radiation flux and energy budgets, (4) soil moisture variations and (5) soil particle (and fugative dust) movement as influenced by collector location. The very limited duration of Phase I does not permit the development of long term biological studies, however, some biological changes might be observed in the two or three months following completion of a few of the solar collector simulators.

If some precipitation occurs this fall, which is not a certainty, we can expect to see some variation in the pattern of germination and development of desert ephemeral plants. Accompanying this vegetative productivity, which may also be exhibited by variable leafing out of the desert shrubs, may be changes in population concentrations of some of the desert insects, e.g., ants. Variations or changes in larger animals such as rodents or reptiles will not occur in the short time span of Phase I although lagomorphs (rabbits) may be attracted to the site. Continuation of microenvironmental modification by the solar collectors beyond the end of Phase I should enhance the possibility of determining animal response to the collectors as well as more extensive changes in shrub phenology and physiology that in turn will cause additional direct responses by other animal groups.

Phase I was designed as an assessment of the possible impacts of solar energy conversion on the desert ecosystem. Between the development of conceptual impacts based on an extensive literature search and on the very limited collection of field data showing changes caused by shelters in the desert, Phase I should be successful in leading the researcher of desert ecosystems to the problem areas that need to be studied more extensively and intensively. These problem areas can readily be described in hypothetical statements or as questions. To more accurately assess the impacts by solar conversion systems, these hypotheses should be tested or the questions answered.
PROJECT COMPLIANCE AND PRINCIPAL INVESTIGATOR EFFORT

During the first four months of Phase I of this project, the research has followed along the lines originally proposed. If there has been any deviation, it has been in the travel schedule of the principal investigator. We had proposed visiting the various industrial concerns that are doing research and development in solar collector design. In communicating with some of these companies, we have found that they are willing to discuss some of their specifications but have discouraged any visitation. This lack of being able to visit the companies has not greatly detracted from the progress of this project.

We have also felt that it was necessary to build solar collector simulators in order to obtain basic ecological impact data. These were proposed in the original proposal.

The principal investigator's effort on this project has followed that presented in the original proposal. He spent two summer months helping in the literature search and in establishing the desert study site. He continues to devote more than 15% of this time during the academic year to this project.
LITERATURE CITED


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