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Detection of Soil Moisture by Remote Surveillance

Difficult problems limit immediate applications, but the potential social benefits call for serious attempts at their solution

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One of the primary resources upon which man directly depends for his existence is soil moisture. Since without it no food can be produced, the distribution of moisture over the land surface of the globe has shaped the development of civilizations and directed much of the course of history. This resource, among others, man now seeks to monitor from space, and toward this end he is applying some of his most sophisticated technology and management expertise.

At the most basic level soil moisture sustains the many crop plants that man cultivates; its presence in proper amounts is essential for seed germination, crucial early development, and successful maturation. It is also important in partitioning water income from rainfall and irrigation into runoff, deep percolation, and storage. Subsequent evaporation of stored water from the soil surface or through vegetation is further dependent on the soil's water content, as is erosion of the soil by wind. On a more complex level, soil moisture influences crop productivity through its effects on insect pests and plant diseases. Thus, a change in the amount of water in the soil may have both good and bad effects. In this paper we attempt to illuminate some of these relationships and to show how soil-moisture data acquired by remote sensing from aircraft or satellites may be used to improve human life.

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Measurement techniques

Three general regions of the electromagnetic spectrum are being used today in feasibility studies of remote sensing of soil moisture—the visible, or short-wave, region; the thermal, or long-wave, region; and the radar, or microwave, region. All offer promise for particular applications, and we will consider briefly some of these uses and the status of research in each area.

It has been recognized for some time that the ratio of reflected to incoming solar radiation (albedo) depends on the amount of water in surface soil. Little thought was given to the predictive value of this relation, however, until Bowers and Hanks (1965) and Clark and Bowen (1967) conducted detailed studies of the spectral reflectance properties of several soils containing different amounts of water. They found good relationships between reflectance measurements and water content, but the practicality of the technique was not thoroughly explored.

It was not until recently that Idso and his colleagues (1975a) put the short-wave radiation technique into a realistic framework by using simple solarimeters in the field in Arizona. They correlated albedo values (normalized to remove solar zenith angle effects) with gravimetrically measured water-content values of soil layers in Avondale loam, extending from the smooth bare surface to various depths (see Fig. 1). For all layers in the upper 2 centimeters, the results were independent of season and indicated that, for the soil studied, normalized albedo was a linear function of the water content of the soil surface.

In addition to monitoring water content per se, Idso and his colleagues (1974) showed that albedo measurements could also be used to delineate the three classical stages of soil drying. In the first of these stages, evaporation proceeds at the potential rate dictated by atmospheric conditions. In the second stage, as the soil dries, its hydraulic conductivity decreases to the extent that it can no longer supply water to the surface fast enough to meet the atmospheric demand, and the evaporation rate begins a precipitous decline from the rate of the first stage. In the final stage, the evaporation rate again levels out, but at a very low rate that gradually approaches zero over a long period of time.

Figure 2 shows the albedo variations of an Avondale loam proceeding through the three stages of soil drying in a single day. Similar relations can be expected for most other soils (Idso and Reginato 1974), with the albedo of a wet soil being about half that of the same

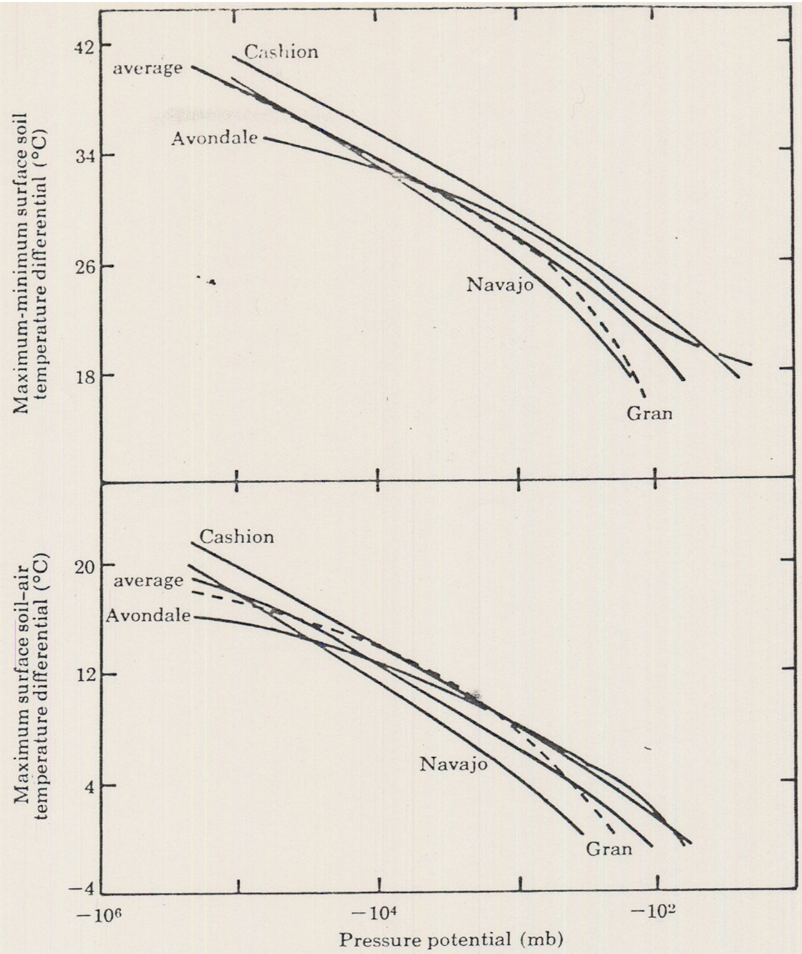


Figure 3 The difference between daily maximum and minimum surface soil temperatures *(top)* and the maximum value of the surface soil-air temperature differential *(bottom)* are plotted against the mean daylight soil-water pressure potential of the top 2 cm of four different soils. Cashion is silty clay; Gran, sandy loam; Avondale, loam; and Navajo, clay. (After Idso et al. 1975b.)

hope for evaluating soil moisture by microwave radiation techniques derives from the fact that the dielectric constant of water at microwave frequencies is quite large (as much as 80), whereas that of dry soil is typically less than 5. Poe and his colleagues (1971) found that the emissivity of a smooth bare field of Avondale loam ranged from 0.5 when very wet to over 0.9 when very dry. Blinn and Quade (1972) observed effects of similar magnitude in measurements made on smooth sandy soils.

A wide range of wavelengths has been used in feasibility studies of soil-moisture detection by microwave techniques—from fractions of a centimeter to tens of centimeters—and the depth of the soil layer monitored has varied from a few millimeters to a few centimeters. For wavelengths ranging from 0.8 to 21 cm, Poe and his coworkers (1971) found that the emissivity variation between wet and dry soil steadily increased. Similarly, Schmugge and his colleagues (1974) found that a 1.55-cm radiometer could not detect variations in gravimetric soil water below about 0.15 for a sandy loam and below 0.15 to 0.20 for a clay loam, but a 21-cm radiometer could discriminate the entire 0.35 range, and do so independently of soil type. At this longer wavelength, the measurement technique was sensitive enough to detect a 2.2°K decrease in brightness temperature (temperature × emissivity) for each 1 percent increase in soil moisture.

Utilization of these seven soil-moisture detection techniques is not always so straightforward as it may appear, and, at present, complexities limit the application of each technique. Considering first the depth over which mean values of soil moisture may be determined, we note that albedo and surface-temperature methods generally give best estimates near the ground surface. Because they are measures of surface-soil properties, their extension to depths below a few centimeters is quite risky. Microwave brightness temperature techniques, however, seem to work best over larger depth increments, although they cannot determine the integral moisture content of soil layers greater than about 10 cm at the present time.

Surface-temperature and certain microwave techniques hint at the possibility of extracting meaningful information about soil water without knowledge of the soil type being remotely monitored. With surface-temperature methods, however, the necessity of knowing soil emittances is a complicating factor. Emittance may vary from 0.88 or less for sands to about 0.98 for clay and loam. Since the emittance of water is close to 0.97 in the infrared region of the electromagnetic spectrum, the emittance of sandy soils could also be expected to be a strong function of water content. Indeed, the measured emittance of a Plainfield sand varied from 0.94 to 0.88 as the volumetric water content of the upper 2.5 cm dropped from 8.4 to 0.7 percent (Fuchs and Tanner 1968). Variations of this magnitude can introduce errors in inferred surface temperatures as large as 8°C and may lead to faulty interpretations of data about infrared radiance acquired by remote sensing (Jackson and Idso, in press).

Similarly, microwave techniques suffer from the need to know surface temperatures in order to resolve moisture-induced emittance changes, and albedo techniques always require specific knowledge of the soil type being viewed. Thus,

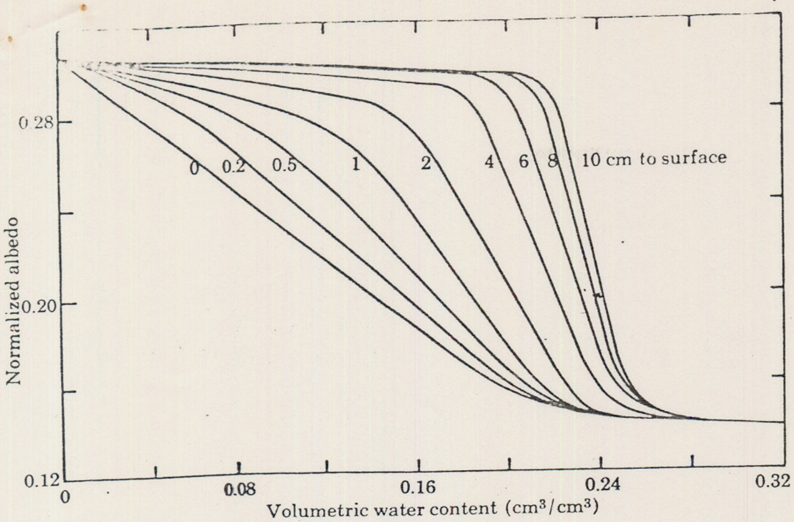
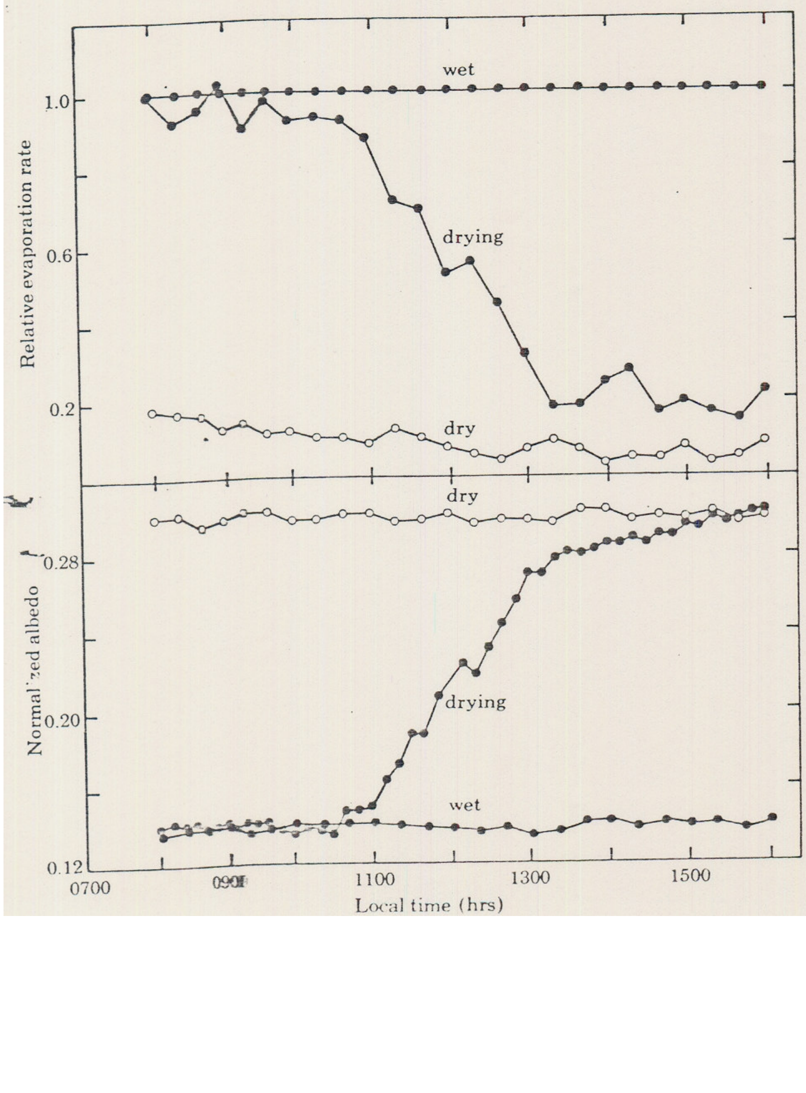


Figure 1. Albedo, normalized to remove solar zenith angle effects, is plotted against average volumetric water content for nine different layers of Avondale loam, with the smooth flat surface as the upper boundary. (After Idso et al. 1975a.)



soil when dry. Based on these findings we have developed a procedure for calculating the daily rates of evaporative water losses from a field, with only an estimate of potential evaporation required as additional input.

Initial attempts to use long-wave radiation techniques to correlate soil moisture with remotely sensed surface temperatures were only qualitative. Myers and Heilman (1969), who reviewed many of these early studies, found that wet soils generally were cooler than dry soils during daylight hours but were warmer than dry soils at night. These results suggested that a thermal inertia concept could be used to monitor soil moisture—i.e. soil temperatures are measured when they are maximum and minimum, and the difference between them is related to water content.

Idso and his coworkers (1975b) recently tested this technique on four different soils, ranging from sandy loam to clay. They found that the postulated correlation between daily maximum and minimum surface-soil temperatures and soil water was well defined for each soil, being linear for soil layers 2 and 4 cm deep but curvilinear for more shallow layers. In addition, they found that all four soils were satisfactorily represented by a single relation when tension between soil and moisture was substituted for water content, and that the maximum value of the surface soil–air temperature differential could be used in place of the difference between daily maximum and minimum surface-soil temperatures (Fig. 3).

The governing principle that offers

Figure 2. Relative evaporation rates and normalized albedos are shown for a very wet, a very dry, and an initially slightly moistened Avondale loam. The slightly moistened soil progresses through three stages of drying. In the first stage it behaves and looks like a very wet soil, evaporating at the potential rate of atmospheric demand. In the transitional stage the soil is no longer able to transmit water from deeper depths to the surface at a rate fast enough to meet the atmospheric demand. At the beginning of the third stage the drying soil looks and responds like the very dry soil, evaporating at a low, near-constant rate.

the extent to which all three of these techniques may be used is still uncertain.

Cloud cover is another problem often encountered in satellite-based remote-sensing programs. Both short-wave and long-wave soil-moisture detection techniques are thwarted whenever clouds obscure the earth's surface. However, there is some indication that clouds may not affect microwave techniques, because natural microwave emission from the ground is only slightly attenuated when passing through clouds (Poe et al. 1971; Tomiyasu 1974).

A problem unique to the microwave technique is caused by salinity. Paris and his colleagues (1972) have shown that microwave emission depends heavily on salinity. Experiments by Nakayama and his coworkers (1973) on Avondale loam indicated that salt concentration gradients are often very steep near the surface of a field soil after irrigation. How such distributions may affect interpretation of microwave measurements is not yet known.

The presence of vegetation creates a problem for all three techniques. At the present stage of development, these techniques can be used only for bare soil. Owing to its ability to penetrate clouds and to significant soil depths, the microwave technique may yet be developed to cope with vegetation. Also, the long-wave technique may make it possible to infer changes in soil water from variations in the temperature of the plant canopy caused by gradations in plant water stress. However, this hypothesis, as well as many others that indicate great potentials for these techniques, has yet to be substantiated. Only intensive experimentation on the ground will determine whether our hopes are well-founded or wishful thinking. The projected uses for the several techniques indicate that the required research investment is not only warranted but urgently needed.

Prediction of crop yields

One of the primary benefits of remote detection of soil moisture would be prediction of agricultural production. Forecasting is an activity of major economic importance, practiced in virtually all countries. Indeed, yearly governmental expenditures for forecasting are about $40,000,000 for the United States and $100,000,000 for the world (Castruccio and Loats 1974). The investment is justified because precise foreknowledge of harvests allows governments to formulate domestic and foreign policies whose effects greatly transcend the monetary outlay. The yearly net loss in social wellbeing due to error in production forecast for United States grain crops alone, for instance, is calculated for the economic model of Hayami and Peterson (1972) to be about $300,000,000 for each 1 percent forecast error. Hayami and Peterson's results indicate that the social returns of money invested in crop-forecasting research are comparable to the returns in such high-payoff agricultural research as hybrid corn studies, where the benefit-cost ratio is near 70, and poultry studies, where it is about 20.

In one of the world's most sophisticated forecast systems—the USDA's Statistical Reporting Service—future crop production is calculated from the crop's condition at the time of estimate, the previous two months' precipitation, the predicted precipitation of the next two months, and the length of time between the estimate and the harvest date. Thus, rainfall is assumed to be the principal determinant of yield. However, if soil moisture is substituted for rainfall, three opportunities for improved crop forecasting present themselves. First, not all rainfall is available for crop use, as some runs off the land and some is lost to deep percolation; soil moisture is much more directly related to crop development than is rainfall per se. Second, rainfall can be measured accurately only in situ, and only a fraction of the total crop land can be satisfactorily sampled for this parameter. In contrast, all crop land has the *potential* to be evaluated for soil moisture by remote-sensing techniques. Third, rainfall may at times be excessive and actually reduce crop yields, whereas prediction based on soil moisture would account for this adverse effect.

Baier and Robertson (1968) have shown that soil moisture is a far better predictor of crop yield than is rainfall: it exhibits higher correlation coefficients, lower coefficients of variation, and lower standard errors of estimate. More yield-prediction models now use soil moisture rather than rainfall. Bauer (1972), for instance, evaluated soil moisture in relation to spring wheat production in the northern Great Plains: based on 871 separate field studies of fallow and continuous cropping systems from 1909 to 1962, he found that each inch of stored water at seeding time contributed about 2.4 bushels per acre to the final harvest. This contribution was somewhat dependent on soil fertility, soil management, and soil texture, and varied from extremes of 1.3 to 2.6 bushels per acre for each inch of stored water. In addition, Bauer found that each inch of growing-season rainfall increased yield about 2.4 bushels per acre. Similar relationships have been reported by Leggett (1959) for winter wheat in the Pacific Northwest and by Staple (1964) for wheat in the central Great Plains. Short-wave and long-wave radiation techniques could assess the stored water at seeding time, when fields are essentially bare, and microwave techniques may possibly assess water added by rainfall during the growing season.

Further research is required to ascertain whether the relations determined by Bauer, Staple, and Leggett are applicable to the other great wheat-producing areas of the world. For instance, only 1 percent of the agricultural land of the Soviet Union lies in areas with an annual rainfall of 70 cm, whereas fully 60 percent of farmland in the United States does (Schertz 1974). Stanhill (1973) has shown that such climatic differences may well elicit different responses to similar variations in water supply. The need to know such relations for different climatic areas and to develop the remote-sensing operational system so that it can acquire the necessary data to use them is borne out by the fact that the 20 million tons of wheat imported by the Soviet Union in 1972–73 is only slightly below the 20.7 million tons forecast for world wheat reserves in 1973–74. Thus a crop failure in only one of the major wheat-producing countries in the next few years could throw the world food market into turmoil; and in view of the recent changes in major world weather patterns, such a failure seems likely.

Techniques of predicting crop yields are also of great use when applied in retrospect to determine reasons for variation in final harvests, since yield variability is very important in land-use planning. An excellent example of this application is the agroclimatological study by Perrin de Brichambaut and Wallen (1963) which assessed the possibilities of dryland farming throughout the Near East. Similar proposals for the drought-stricken Sahel have recently emerged from the Niger meeting of UNESCO's Man and the Biosphere program.

Prediction of pest outbreaks

The water content of the soil is the most basic ecological factor in the development of insects that spend part of their life cycle in the soil (Chauvin 1967). Because it influences fecundity, rate of development, and survival at various stages, knowledge of soil-water content can greatly assist man in coping with the various insect pests that regularly ravage his farmlands.

An important case in point concerns the desert locust, *Schistocerca gregaria* Forsk., which has been a problem from time immemorial. Normally, only small numbers of this insect infest the central parts of its potential invasion area—from the Sahara to northern Iran. Periodically, however, it breeds in astronomical numbers and spreads over Africa and Asia, creating economic havoc in developing nations by destroying vital crops. An individual swarm of these locusts may cover 100 km^2 at any given time.

The desert locust usually deposits its eggs just beneath the ground surface, and the development of the egg is entirely dependent on the absorption of moisture from the surrounding soil (Rainey 1969). Indeed, in order to hatch, the eggs must absorb their weight in water, ideally in the first five days after they are laid. Often, because breeding areas are uninhabited and normally arid, they remain undiscovered until the swarms escape to plague the farmers of more mesic sites, at times across distances of up to 3,500 km (Rainey 1973). Then, when great harm has already been done to valuable crops, the only effective way to combat them is by the airborne application of pesticides, which compound the damage by contaminating man and his animals.

A global program of remote assessment of the water content of surface soil could detect unknown breeding areas. These are characterized by high levels of soil moisture after the rains, which are accompanied by winds that draw the locusts into the areas. Early detection would allow poison-baiting campaigns to be waged against the young wingless "hoppers" before they fledge into the winged adult stage when airborne pesticide applications are required.

If it is impossible to reach the breeding areas in time, recurrent monitoring of the surface soil moisture could be crucial in forecasting fledging dates and alerting local officials to the need for an early pesticide application before damage becomes too widespread. Prediction could be based on calculating the rates of locust egg development in the soil and the early growth of young hoppers, which depend on soil moisture and on the development of rain-induced ephemeral vegetation. The feasibility of such a program has recently been demonstrated by Pedgley (1974), who used ERTS-1 (now Landsat-1) data to locate a 500-km^2 area on the Red Sea coastal plain of Saudi Arabia within which the desert locust had produced several small swarms. Identification of this area with ERTS-1 data, however, was based on vegetation discrimination. Soil-moisture assessment would allow potential breeding sites to be identified much earlier, thereby improving the effectiveness of campaigns against the locust.

Recent climatic changes underscore the need for a detection program, particularly in light of the risk of famine in much of the locusts' potential breeding area. The earth has been cooling slightly since about 1940 (Mitchell 1963), and in the past few years, this cooling has apparently led to an equatorward extension of the circumpolar vortexes—the great undulating bands of high-altitude winds that revolve about the poles from west to east. In the Northern Hemisphere, this shift has resulted in a southerly displacement of the great desert-forming high-pressure zones. The outflow of descending dry air from these zones has prevented the moisture-laden summer monsoons from penetrating grazing lands that depend on them for their yearly recovery from seasonal winter droughts. Thus, the southern border of the Sahara Desert, the traditional home of the desert locust, has expanded southward and eastward in the last few years, and droughts have occurred all the way from the Middle East into India and China.

While droughts may tend to displace the desert locust into new areas at the southern extreme of the Sahara Desert, rains may do likewise, with even more disastrous effects, in the north. The same weather patterns that pushed the summer monsoons southward also pushed rains that normally fall in the Mediterranean Sea hundreds of miles farther south into North Africa. A great danger exists in this region and elsewhere, because, in addition to being taken to areas of regular seasonal rains, the desert locust can be moved by winds to areas of anomalous rains in regions that are sometimes even more arid than their traditional breeding grounds (Rainey 1969). Advance warnings of impending outbreaks obtained by remote sensing of soil moisture could aid in preventing the destruction of badly needed crops.

The desert locust is only one of many crop pests dependent on soil water. Of the locusts, there are also *Dociostaurus maroccanus* (Thunberg), which lives chiefly in the Mediterranean countries and northwest Africa; *Locusta migratoria* (L), with various races of subspecies covering at times southern Europe, nearly all of Africa, Madagascar, southern Asia, the East Indies, New Zealand, and parts of Australia; *Schistocerca paranensis* (Burmeister), which ranges throughout most of South America, Central America, southern Mexico, and occasionally in some of the West Indian islands; *Locustana Pardalina* (Walker) and *Nomadacris septem-*

ally, when soils are moist, a varied population of beneficial bacteria somewhat mitigates harmful effects of soil-borne plant pathogens. Clark (1967), however, has found significant reductions in this mitigating influence at pressure potentials of −3 bars or less; and Cook and Papendick (1971) indicate that antagonism by this entire group of beneficial organisms may not exist at soil-water pressure potentials below −10 to −15 bars.

Host-pathogen relationships are also affected by pressure potential changes. Edmunds (1964), for instance, has noted rapid progressions of charcoal rot of sorghum caused by *Macrophomina phaseoli* (Maubl.) Ashby, while Ghaffar and Erwin (1969) have noted the same for cotton. Water stress apparently triggers the sudden proliferation of latent infections in sorghum.

Another interesting host-pathogen relationship involves vascular parasites. As soil moisture decreases, a critical point is reached at which transpiration is significantly reduced, and Cook and Papendick (1971) have indicated that this slowing of the rate of water movement through the plant may completely stop the upward spread of the pathogen or at least slow it enough for host occlusion reactions to seal it off. This would explain why vascular diseases are characteristically more severe in wet than in dry soils.

A third host-pathogen interaction that depends on soil water involves host exudation of nutrient solutions that affect development of pathogenic fungi as well as that of the general soil microflora. Depending on the resultant pathogen-antagonist relations, a change in the amount of water in the soil can cause this mechanism either to help or hinder the host plant. For example, Kerr (1964) found infection of pea seed by *Pythium ultimum* increased with greater soil-water content, owing to the loss of sugars from the seeds, while Bumbieris and Lloyd (1966) showed that nutrients influenced the rate of hyphal lysis and Cook and Papendick (1971) noted that a richer and more varied nutritional environment in the vicinity of root exudates supported a more active and varied soil microflora that increased the chances for antagonism.

Soil water generally affects pathogen-carrier relationships most significantly when the carrier is a migratory species. Many plant viruses are spread by insects that directly depend on soil water at some point in their development. In the case of the beet leafhopper vector, *Circulifer tenellus* (Baker)—which harbors the curly-top virus that infests sugarbeets, beans, tomatoes, and other crops—a hot, dry summer will eliminate most of the host plants on its desert breeding grounds, reducing the spread of the insect (Carter 1930). Remote assessment of soil moisture in the breeding areas could indicate where major outbreaks of the disease, and other similarly transmitted diseases, might be expected, as well as which replacement species would compete best in an eradication program of the host plants.

A good example of such considerations is a 1959 study at Twin Falls, Idaho. After much preliminary work on a succession of desert plants and their ability to compete in soil with little moisture, 200,000 acres of range were reseeded with crested wheat grass to replace Russian thistle, the summer host of the beet leafhopper. Insect populations were reduced to an unimportant level, where previously the beet leafhopper and curly-top virus were limiting factors in the production of sugar beets, tomatoes, and beans (T. J. Henneberry, pers. comm.).

Although control of soil moisture may help in the struggle against soil-borne plant pathogens, responses of the plants themselves must also be carefully considered. For example, water stress is apparently critical to potato production during tuber formation, and although Lapwood and his colleagues (1970) indicate that lighter irrigations before and after this period might control common scab, the work of Thorne (1942) shows that light irrigations at this time may increase damage by rootknot nematodes.

In spite of such examples, information on soil moisture often can initiate straightforward preventive measures. Almost forty years ago, Ezekiel (1938) found a correlation between early-season rainfall and the amount of root rot that subsequently developed in cotton that allowed losses to be forecast several months before harvest. Remote sensing of soil water content near the time of plant emergence, when the soil is essentially bare, could accomplish the same goal more efficiently. Leach (1938) showed that similar predictions may be feasible for the activity of soil-borne *Sclerotium rolfsii* Sacc., which attacks sugarbeets, and Fink (1948) found similar correlations for *Aphanomyces cochlioides*, the black root rot of sugarbeets.

Another clear-cut finding is the host-pathogen relation of spring wheat and rust fungus. Spring wheat planted in Arizona in December reaches its most critical period for moisture at the jointing stage in the spring; stress at later times, such as during flowering and after full kernels have formed, is less detrimental to yield (Day and Intalap 1969). Where the rust fungus *Puccinia graminis* is a hazard, Cook and Papendick (1972) suggest an irrigation program that alleviates stress during the critical growth stages but allows drier interim periods. Similarly, the critical stress period for sorghum is shortly after bloom (Edmunds 1964), and irrigation at this period may prevent charcoal rot. Remote detection of soil moisture could allow a close watch to be kept on soil water so that irrigation could be used to combat these pathogens.

Management of crops and rangelands

In addition to decisions related to crop pests and plant diseases, many other management problems are linked to soil moisture. The planting of most crops is highly dependent on soil moisture. Although the water supply is usually adequate within a few centimeters of the soil surface, the depth to moist soil varies, and the surface soil itself is often too dry for satisfactory germination and emergence of seedlings. Clark and Bowen (1967) have noted that if soil-moisture conditions prevent the uniform emergence of cotton, production costs rise significantly, as the farmer must replant *fasciata* (Serville), which inhabit the southern half of Africa; and *Melanoplus mexicanus mexicanus* (Saussure) (= *Melanoplus spretus* [Walsh]), which used to occur in enormous numbers in the midwestern United States.

Many of these locusts breed for years in the solitary phase in comparatively small areas of low rainfall. However, when increased rainfall stimulates more luxuriant vegetation, they multiply profusely, increase their habit of aggregation, transform into the gregarious phase, and finally spread over the surrounding areas, often for hundreds of kilometers. This pattern could be extremely important for the United States because of the present climatic uncertainty, for it is now believed that the former Rocky Mountain locust *(M. spretus)* is the gregarious form of the presently widely distributed *M. mexicanus* (Williams 1957).

Some change in the environment has prevented the development of the gregarious form since the end of the last century—very possibly reduced rainfall. Many of the goldseekers who made the trek to California in 1849 reported endless seas of head-high grass in areas that are practically desert today. If the many meteorologists who predict a return to nineteenth-century patterns of heavier rainfall in the western plains and Rocky Mountain states are correct, there could well be a resurgence of the devastating swarms of *M. spretus* that used to plague this section of the country.

Numerous crop pests other than locusts depend on soil water at some time in their life cycles. Rainey (1973) mentions plague grasshoppers of the species *Aiolopus simulatrix* Walk., a major pest of the *Sorghum* millet widely grown as a staple cereal, and the African armyworm, *Spodoptera exempta* Walk., whose attacks on cereals and grazing lands in eastern and southern Africa at times approach the severity of a major locust invasion. Similar outbreaks of the moth *S. mauritia* (Boisd.) occur in India after the first heavy summer rains, where wild grasses and young rice plants are the objects of attack (Ramakrishna Ayyar and Anantanarayanan 1935).

Other moths also seem to migrate toward and within zones of low-altitude convergence of winds. Certain invasions of *Agrotis ipsilon* (Hfn.) in the Near East have been associated with warm southerlies and accompanying depressions (Rivnay 1964), and in lower latitudes the initial invasions of *Alabama argillacea* (Hb.) into the Fazenda Sao Miguel cotton-growing area of the Rio Grande del Norte in Brazil appear to coincide with the beginning of the seasonal rains (Davidson 1967). Also, extensive work in China by Lin and his colleagues (1963) on the oriental armyworm, *Mythimna separata*, has shown that invasions of this species represent migration toward a major zone of convergence that lies across northern China in summer.

One reason why remote sensing can be so helpful in predicting outbreaks of crop pests is that the tenacity with which water is held by the soil—i.e. soil-moisture potential—rather than water content alone determines insects' reproductive success (Maelzer 1961). This is extremely significant, for although the amount of water in the soil cannot be determined from space without knowledge of the type of soil viewed, recent work by Idso and his colleagues (1975b) indicates that the pressure potential of soil water may be discriminated if temperature can be measured accurately. (Pressure potential is the work per unit mass of water required to move it from a free water source to a point in question. Pressure potentials are always negative. The commonly used terms *tension* and *suction* are numerically equal but opposite in sign to the pressure potential.) Thus, remote sensing of the pressure potential—the soil water property of most direct importance to insect reproduction—is at the stage where actual field applications should be tested.

A final example of pest behavior well suited to remote surveillance concerns *Aphodius tasmaniae* Hope, an indigenous beetle which has been an economic pest in improved pastures in southern Australia for about thirty years. This insect is attracted to relatively bare areas to lay its eggs, thus eliminating bothersome effects of vegetation in remote analyses of soil water. Maelzer (1961) has shown that the moisture content of the top centimeter of soil is the most important factor in promoting or inhibiting aggregations of adults—and this surface layer is the easiest to assess accurately with remote sensing. Also, his experiments showed that, on soil ranging from sand to clay loam, soil-water pressure potential affected aggregation, life span, and fecundity more than water content alone.

Prediction of plant disease

Water content is one of the most important aspects of the soil environment influencing the growth and survival of soil-borne plant pathogens (Cook and Papendick 1971). The moisture status not only directly affects the rates of pathogenic activity but it also influences them indirectly through pathogen-antagonist interactions, host-pathogen interactions, and pathogen-carrier interactions.

Direct effects of soil-water stress on pathogenic fungal growth are generally minimal over the pressure potential range from 0 to −15 bars—or from saturation to the permanent wilting point of plants. However, there are often large negative values of pressure potential in surface soils that limit fungal parasitism in this range. Dryland wheat in the Pacific Northwest of the United States, for instance, remains turgid as plants approach maturity in June and July by drawing moisture from soil 1 to 2 meters deep, while soil-water pressure potentials of −50 to −100 bars often develop in the top 15 to 30 cm of soil. Likewise, seeds planted in very dry soil are not as subject to fungal attack, nor are crops grown on elevated beds in furrow-irrigated fields. In addition to these direct effects on pathogenic fungi, low water contents also affect solute diffusion and soil aeration, which in turn determine the mobility of bacteria and zoospores and certain chemical reactions important to the pH of soil water (Griffin 1970).

The effects of soil water on pathogen-antagonist relationships are often more important than direct effects on pathogen activity. Generor perform additional cultivation and thinning, or both. Remote surveillance of fields intended for cotton could take much of the uncertainty out of these operations. Clark and Bowen suggest that attaching an albedo sensor to the front of the vehicle used to pull the planter could provide a continuous measure of surface-soil moisture that would control planter depth and press-wheel pressures.

The recent rises in the price of petroleum have triggered a worldwide shortage of nitrogen fertilizers, which means, among other things, that existing supplies must be used as efficiently as possible. Bauer and his coworkers ([illegible]) have shown that soil moisture at the time of seeding is the best guide in determining nitrogen fertilizer needs of nonleguminous crops in the northern Great Plains. If current proposals for a world food bank, including stores of fertilizer, are put into effect, a global program of remote soil-moisture assessment would be a great help in determining a system for the disbursement of fertilizer stocks.

For several reasons residence times of pesticides in soil depend greatly on soil water. First, these chemicals can degrade biologically only if soil moisture is sufficient to support significant populations of microorganisms that can break them (Messersmith et al. [illegible]; Hamilton and Arle 1972). Some pesticides tend to move to the surface with the upward mass flow of water induced by surface evaporation and to be volatilized there; [illegible] (1969) has termed this process the "wick effect." Third, whenever there is enough water in soil to provide more than one molecular layer of water for adsorption on all soil particles, water competes strongly with many pesticides for adsorption sites; this increases the chemical's vapor concentration and hence its volatilization (Spencer 1970; Igue et al. 1972).

Because of the effect of water content on residence times of pesticides in soils, remote detection of soil moisture has implications for farm management. For example, a rapid assessment of a field's water content could tell the farmer whether herbicide or insecticide application

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1974) and indirect damage by dispersal of plant pathogens (Claflin et al. 1973).

Even people are affected by the dispersal of pathogens: there is a high incidence of coccidioidomycosis, the "valley fever" of the arid southwestern United States, following the spread of the dust-borne human pathogen *Coccidioides immitis* by the huge duststorms that regularly sweep across this region in summer and autumn. Both man and animals all over the world are affected by dust-borne *Cryptococcus neoformans*, which stimulates brain tumors and attacks skin, lungs, and other organs (Conant 1965). In addition, windblown dust constitutes a hazard to both land and air travel. Knowledge of soil-moisture conditions over the earth's arid and semiarid regions is a prerequisite to the intelligent confrontation of a whole spectrum of problems arising from the effects of windblown dust.

Undoubtedly, there are many other applications for soil-moisture data. Rango and his coworkers (1974), for instance, mention that obtaining information on soil moisture is one of the more difficult problems associated with solving the water-balance equation for river basins. Observations from satellites would make possible a real breakthrough in hydrology.

Various procedures for radiometrically measuring soil water-content from just above the ground surface, from aircraft overflights, and from orbiting satellites complement each other and hold promise for improving efficiency in agricultural production and processing. The techniques utilizing reflected short wave radiation (albedo), emitte
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