Remote-Sensing of Crop Yields

Canopy temperature and albedo measurements have been quantitatively correlated with final harvests of wheat.

Sherwood B. Idso, Ray D. Jackson, Robert J. Reginato

The politics of food will become the central issue of every government. Although many people have criticized the techniques and assumptions used, few have disputed this conclusion of the recent Central Intelligence Agency working paper (*1*) on the potential implications of trends in world population, food production, and climate. There indeed seems to be a consensus that we are living at a time when there is a very delicate balance between the supply of and demand for essential foodstuffs, and that the vagaries of even a "normal" climate could well upset the balance with catastrophic consequences (*2*).

As a result, agricultural research has become one of our most important national assets, exerting a two-pronged attack upon the problem. First, a variety of approaches to yield betterment is being studied and perfected; and second, new techniques for rapid and reliable assessment of global crop yields—to help us determine how best to match supply with demand—are being developed. Remote-sensing techniques play an important role in this endeavor, because of the large areas to be surveyed on a recurring basis.

Perhaps the best known project within this second category is LACIE, the Large Area Crop Inventory Experiment (*3*). In this program satellite-borne sensors are used to determine the reflected solar radiation in various wavelength intervals; these measurements can be used to estimate acreages planted to different crops, and then statistical and climatological yield prediction models can be used (*4*) to arrive at final harvest figures. These yield models, however, are not true remote-sensing models, because they require input data that are generally obtained from ground-based measurements. In this article we report the development of a "stress degree day" concept based on the use of emitted thermal radiation that has a sound agronomic basis and that appears suited to a more complete remote-sensing program. Used in combination with acreage estimates of the type made in the LACIE program, it could form the basis for a viable system for the remote surveillance of crop production.

Background

The two primary environmental determinants of crop yield are temperature and moisture. Although it is possible to control both of these factors to some degree in small-scale applications, with the use of greenhouses, plastic mulches, irrigation, and the like, most of the world's agriculture is dependent on a favorable set of circumstances with respect to both of these factors. Thus, remote-sensing of soil temperature and moisture has historically been thought to hold the key to the development of techniques that could be used to rapidly assess global crop yields.

The technology required to remotely measure surface temperatures of both bare soils and vegetated areas is well developed. Complexities may arise from perturbations in the atmosphere between the earth's surface and airborne or space platforms from which measurements are made and from uncertainties in surface emissivity values; however, the first of these problems can be rectified, and the second one is not too important in most agricultural applications because the variation in emissivity among agricultural soils and crops is small (*5, 6*). Thus, the crucial issue for the prediction of crop yields by remote-sensing has been how to remotely assess soil water content and relate this measurement to crop yield.

A review of the work on remote-sensing of soil moisture in bare fields (*5*) indicates that surface temperature measurements may provide information on soil moisture. In a recent study Idso and Ehrler (*7*) have shown that the same may hold true for vegetated fields. Thus, the central question is how to relate surface temperature measurements to crop yields.

During the last few years there has been a sustained research drive in this direction. Several workers (*8*) have used temperature measurements of the plant canopy to detect crops under various degrees of water—and therefore photosynthetic—stress; a number of investigators (*9*) have begun to standardize this way of representing vegetative stress by noting the stress-induced increase of leaf temperature above air temperature. Almost universally, however, the crucial link has not been made between this stress representation and final crop yield. Where it has been made, such as in the wheat yield prediction model of EarthSat Corporation (*10*), the stress index has been derived along more traditional lines of comparing calculated actual to calculated potential evapotranspiration (*4*), and it is dependent upon a number of parameters not amenable to ready assemblage in very accurate form or easily measurable by remote-sensing.

Consequently, we have tried to develop a link between the differential between leaf temperature and air temperature ($T_L - T_A$) and crop yield. Somewhat analogously to the centuries-old concept of the "growing degree day," we have devised a "stress degree day" (SDD) concept, in which the final yield of a crop (Y) is hypothesized to be linearly related to the total SDD's accumulated over some critical period. We express this notion mathematically as

$$Y = \alpha - \beta\left(\sum_{i=b}^{e} \mathrm{SSD}_i \right)$$

where SDD_i is the midafternoon (about 2 p.m.) value of ($T_L - T_A$) on day i, and b and e represent, respectively, the days on which the summation procedure is to begin and end. We explore here the validity of this hypothesis and the use of auxiliary albedo-based methods for determining the critical period over which the SDD concept may be applied. We choose albedo for this purpose, since the remote-sensing of reflected solar radiation from fields planted to certain crops has already been developed to a high degree of sophistication.

Drs. Idso and Jackson are research physicists and Dr. Reginato is a soil scientist at the U.S. Water Conservation Laboratory, Phoenix, Arizona 85040.

Experimental Procedure

Our experiment was conducted at Phoenix, Arizona, on a field (72 by 90 meters) of Avondale loam that was given an initial application of nitrogen fertilizer and then planted to wheat (*Triticum durum* Desf. var. Produra) on 3 December 1975. The field was then divided into six nearly equal rectangular plots oriented north (N) to south (S). On 8 December 1975 (day 5 of the experiment), all six plots were irrigated with 10 to 12 centimeters of water. Except for occasional rain showers which added a total of 4.7 cm of water, the plots received no more water until 24 February 1976, day 83. At that time plots 2 through 6 received between 10 and 12 cm of water each. Thereafter, plot 6 received an extra 10- to 12-cm irrigation every 2 weeks, the last one on 27 April 1976, day 146. Plots 2, 3, 4, and 5 were irrigated so as to produce a gradation of soil water content ranging between the very dry plot 1 and the very wet plot 6 in the order 1, 3, 4, 5, 2, 6. In addition, the south halves of the dry plots 1 and 3 (1S and 3S) were irrigated on day 125, and plot 3S was irrigated again on day 146.

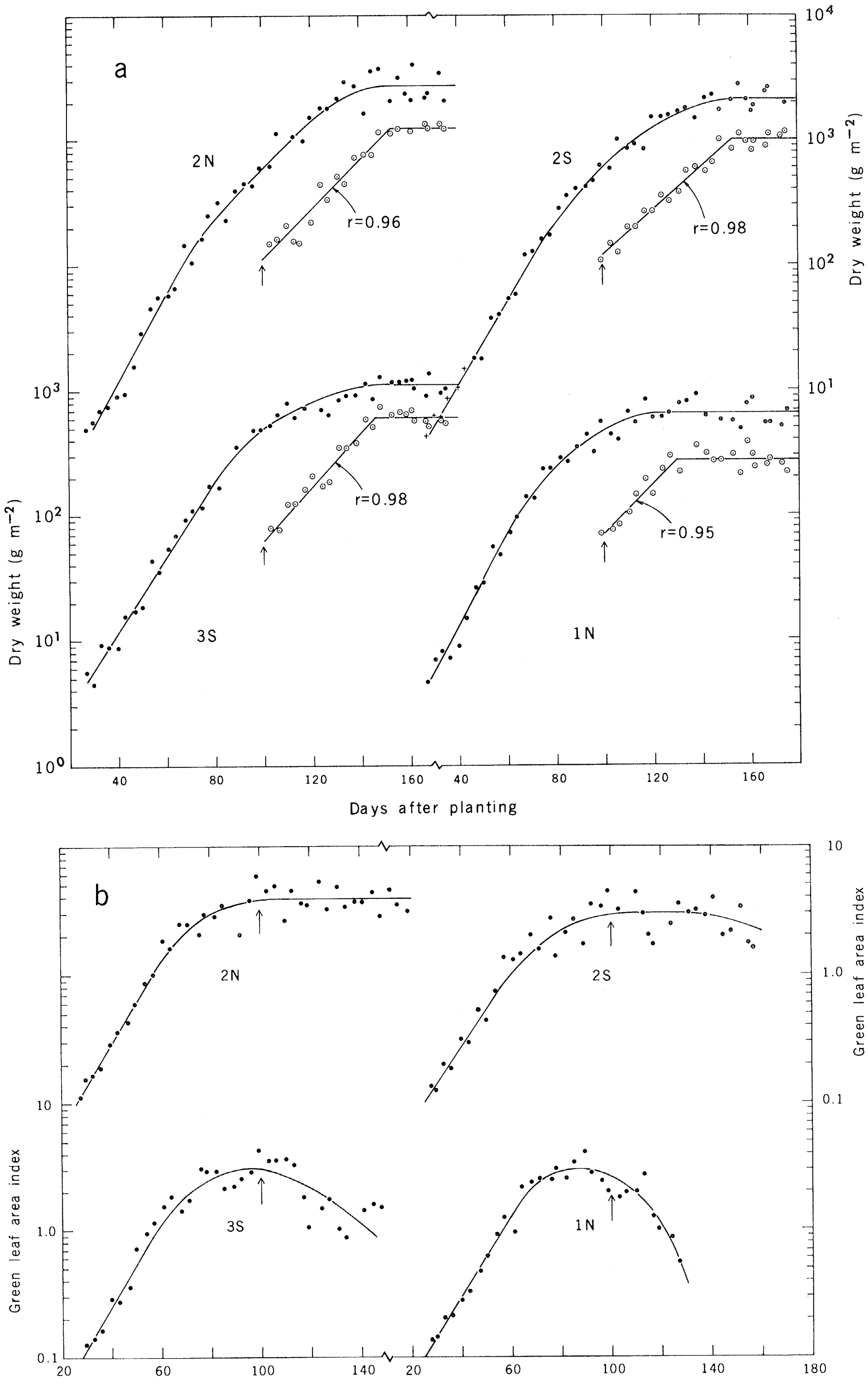


Fig. 1. Seasonal progressions of (a) total aboveground dry weight accumulation (closed circles) and head dry weight accumulation (open circles) and (b) green leaf area index for 4 of the 12 wheat field sites that represent a gradation (2N→2S→3S→1N) from very moist to very dry soil conditions. Short vertical arrows mark the location of day 100.

Separate plant growth characteristics of the north and south halves of all six plots (12 sites) were assessed twice each week throughout the growing season. Parameters sampled under this program included total aboveground dry weight, head dry weight, and green leaf area index (green leaf area per unit soil area). We determined the total aboveground dry weight by cutting off plants from selected portions of the 12 sampling sites at ground level, drying them in an oven, and weighing them. Forty randomly selected plants per site were used at the start of the season for each of these determinations; but, as the crop matured, this number was reduced to ten. Head weights were determined similarly for three plants from each site. Characteristic results obtained for four of the sites that spanned most of the soil water content range are shown in Fig. 1a. The green leaf area index was also determined twice each week for three plants selected at random from each site. This was done by means of an optically integrating area meter developed by Lambda Instruments Corporation (*11*). Results for the same four sites are depicted in Fig. 1b. The per area representations of all parameters plotted in Fig. 1 were based on the hand-harvesting of approximately 14-m² sections of each of the 12 sites and the counting of every plant and mature head produced thereon. The wheat from these 14-m² sections was then threshed to provide final grain yield measurements for all 12 sites.

We measured incoming and reflected solar radiation over the north halves of each of the six plots every 20 minutes throughout the experiment with six pyranometers (Eppley) located about 50 cm above the plant canopy. We converted the daily radiation totals thus measured to mean daily albedo values and subsequently normalized them to account for the varying altitude angle of the sun by using a procedure described by Idso *et al.* (*12*). Figure 2 shows the results for all essentially clear days of the experiment. We measured air temperatures 150 cm above the crop canopy with shielded thermocouples on this same 20-minute schedule.

Every day of the experiment from day 10 to day 168 (except for 4 days missed) we also obtained a number of presunrise and midafternoon (about 2 p.m.) blackbody temperature measurements of the plant canopy at each of the 12 sites with 2° field-of-view (f.o.v.) or 20° f.o.v. infrared thermometers (Barnes PRT-5); in some cases both instruments were used simultaneously. The 20° f.o.v. instrument viewed the plant canopy perpendicular to the ground and at 45° angles to it in the cardinal compass directions; the 2° f.o.v. instrument (which was not used until day 92) viewed the canopy at a glancing angle that allowed only plant parts to be seen, from both east and west directions. We will present these data in the SDD format following an analysis of albedo data required to characterize the critical period for application of the SDD concept.

Albedo and Head Growth

We postulate, on the basis of our final results, that the best time over which to sum daily values of the SDD parameter is the period from the initiation to the cessation of head growth, that is, from the time of the first appearance of awns to the time when the head produces no more dry matter. Can albedo measurements delineate this period accurately enough for our purposes?

An examination of Fig. 2 indicates that certain features stand out vividly. First, there are the albedo recoveries after rains early in the season. These variations are due to the fact that the albedo of a wet soil is only about half that of a dry soil (*13*). The rapid increase in the green leaf area index between day 70 and day 84 almost completely masks this effect after the general irrigation on day 83.

The second most obvious feature of Fig. 2 is probably the dramatic increase in albedo at each site as harvest approached. These increases were visually correlated with a general browning of the crop. In an effort to determine if they had any other physiological significance, we looked closely at the head dry weight data (Fig. 1a). These data appear to be composed of two intersecting linear trends when plotted against time in a semilogarithmic format. We thus subjectively divided the data points for each plot into two groups; we averaged the data points for one of these groups to determine the level of the plateau portion of the head growth curve, and we transformed the ordinate values of the data points in the other group into natural logarithms so that we could carry out a linear regression analysis, designed to specify the slope and location of the ascending portion of the head growth curve. Another linear regression analysis was then carried out between the days of intersection of these two lines for each of the six north halves of the field and the days on which the final albedo increases of each plot occurred. The results yielded a correlation coefficient (r) of 0.981 with a standard error of estimate of less than 2 days. Thus, albedo data apparently can adequately specify when wheat head growth has ceased. But what about the specification of head emergence from the sheath?

The final obvious feature in the albedo data (Fig. 2) is the discontinuity that appears between day 95 and day 105. Checking our library of wheat photographs (36 per week throughout the experiment), we observed that this period corresponded with the time of head and awn emergence. The data of Fig. 1a also indicate that the midpoint of this period, day 100, marked the average beginning date of first head and awn emergence.

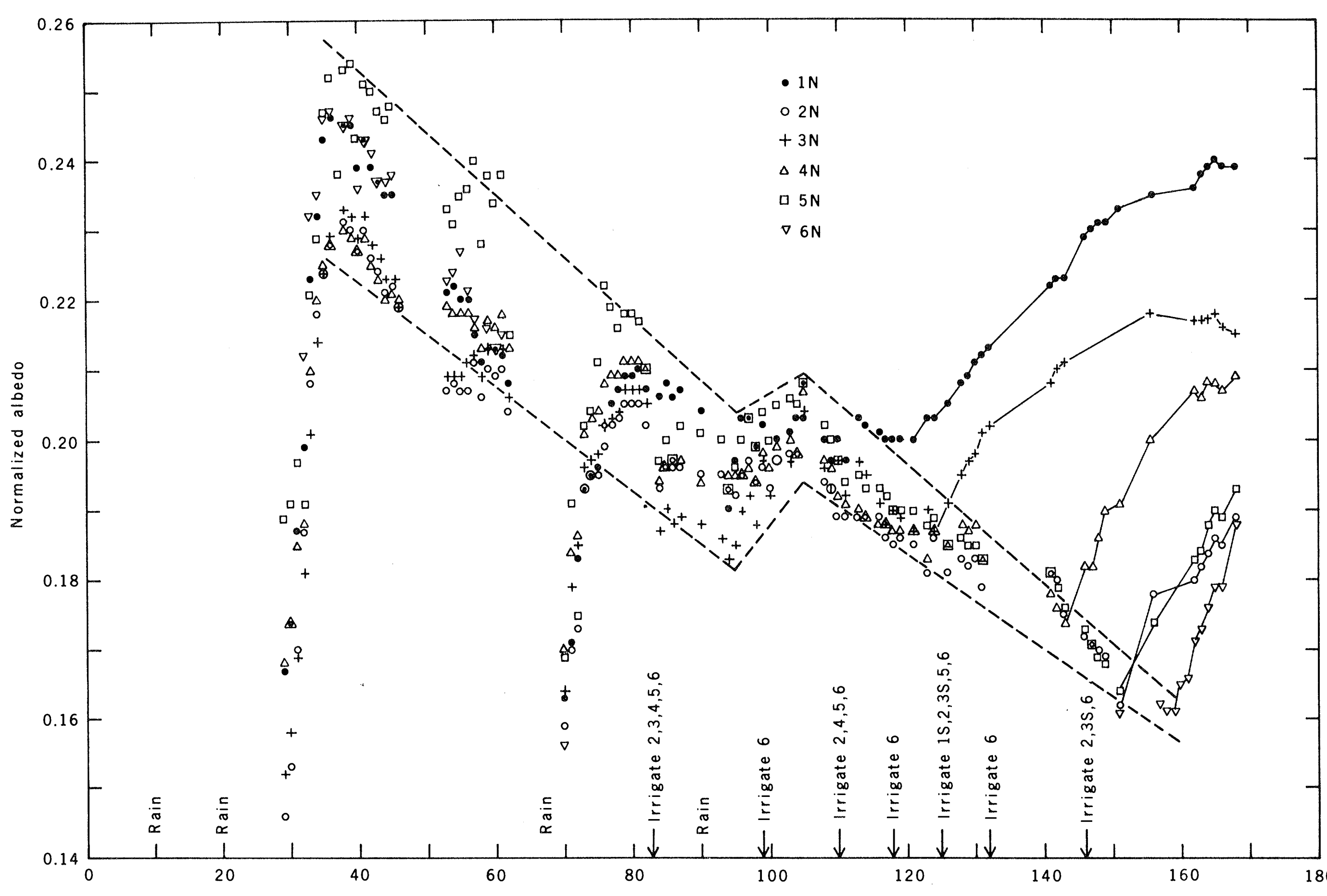


Fig. 2. Seasonal progressions of normalized clear-day albedo values for the north halves of the six plots of wheat, with notations on times of rainfall and irrigation.

Thus, albedo data appear to exhibit characteristic variations enabling us to closely identify both the beginning and end points of the postulated crucial period of head growth.

Testing the SDD Concept

Starting our summations at day 100, we have plotted in Fig. 3 cumulative SDD's for the north halves of all six plots and two of the south halves that started out as dry treatments but received subsequent irrigations (plots 1S and 3S). We have noted (circled) on these lines the days at which head growth ceased, as determined from the actual head growth data. Similar end points are also marked for the south halves of three of the other four plots that were not graphed in their entirety. (Head growth data were insufficient to determine an end point for plot 6S.) The 11 end points together describe a good linear relation between the total SDD's accumulated during the crucial head growth period and the total length of time of this period.

We next plotted final grain yield data for the north and south halves of all six plots (omitting plot 6S) against total SDD's accumulated during the crucial head growth period. This is done (Fig. 4) not only for summations starting at day 100, the best estimate of the start of head and awn emergence from both albedo and growth curve data, but also for four other starting dates that span a range of 15 days. The results indicate hardly any reduction in accuracy from the combined regression line for SDD summations that start at any of the other specified initial days. Thus the SDD concept of yield prediction appears to be basically sound, and the albedo technique for delineating the time period of its application seems to be adequate.

Variations and Extensions

The crop temperatures we have discussed thus far are blackbody temperatures obtained from a 2° f.o.v. infrared thermometer viewing the plant canopy at a glancing angle that allows only plant parts to be seen. This approach is ideal for a farmer, who could make such measurements from a pickup truck going down a road without even stopping; but a plane or spacecraft constrained to view essentially downward may "see" some soil in addition to plants.

From an analysis of the measurements we had made looking straight down at the crop canopy with a 20° f.o.v. infrared

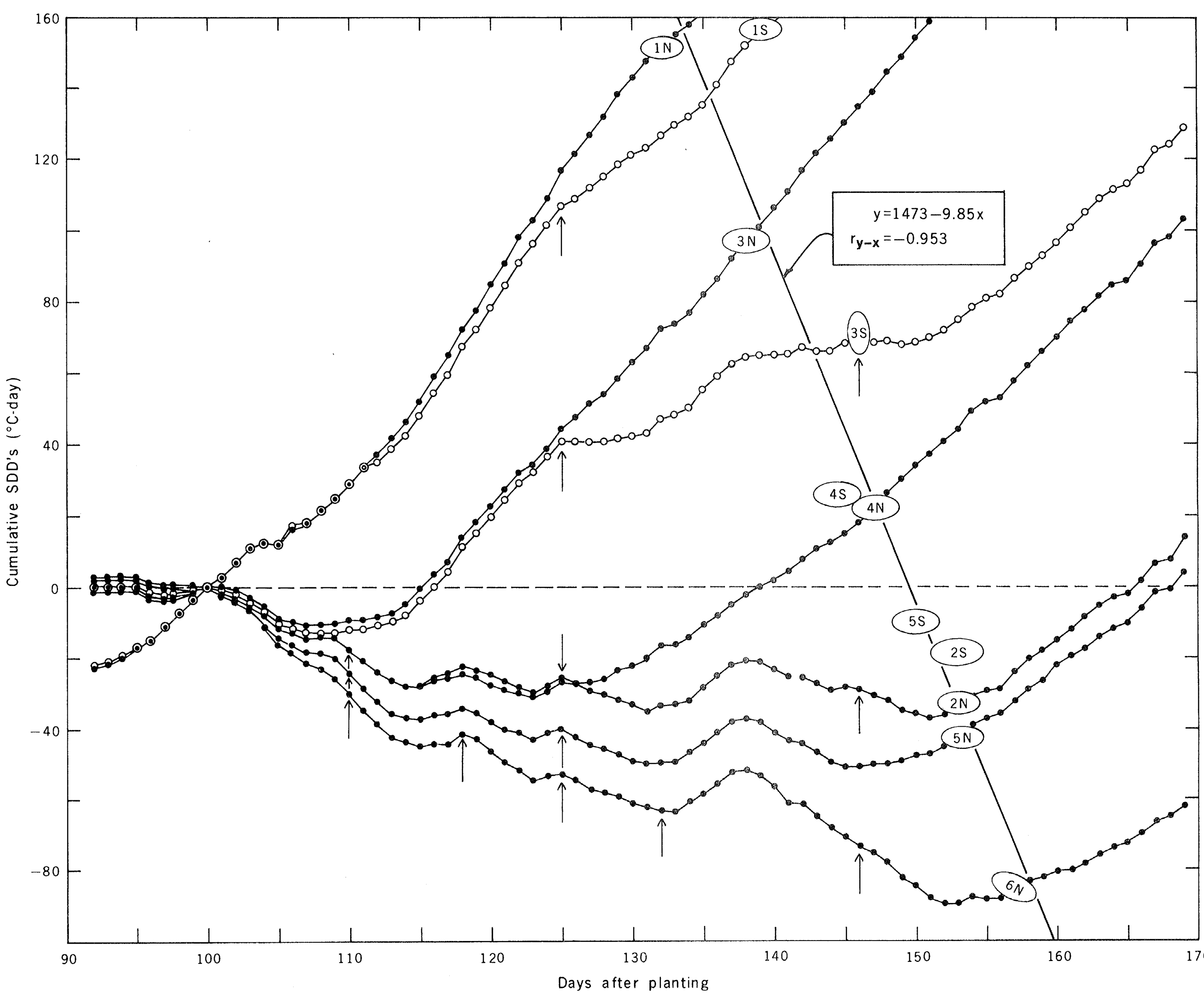
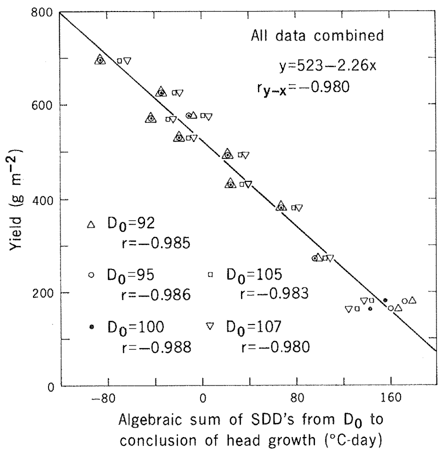


Fig. 3. Seasonal progressions of cumulative SDD's for 8 of the 12 field sites, as determined from midafternoon (about 2 p.m.) measurements of air temperature 150 cm above the crop and canopy blackbody temperature obtained from a 2° f.o.v. infrared thermometer operated so as to view only the plant parts. Arrows indicate times of irrigation. Cumulative SDD's acquired during the period from head emergence to the cessation of head growth are shown for all 12 field sections as circled plot designations.

Fig. 4. Final grain yields for all 12 field sites versus the total accumulation of SDD's from head emergence to the cessation of head growth. Results are shown for five different starting dates (D_0).



thermometer, similar to the data of Figs. 3 and 4, we obtained corresponding regression coefficients of −0.958 and −0.985, respectively, results that are equally as good as our earlier ones (Figs. 3 and 4). Thus, the added complexity of possibly "seeing" some soil when viewing the canopy straight down from above does not appear to present additional analytical difficulties.

A second problem that merits some discussion is the type of air temperature measurement to be used in the SDD approach. This measurement must be made over the crop. For a ground-level operation this is not too much of a problem; for, if one can get to the field to make the remote canopy temperature measurement, then one can get to it to install an air temperature–measuring device or to make an air temperature measurement with a portable device. However, for large-scale airborne or satellite operations, such air temperature measurements may not be available. In that case, we suggest that a thermal inertia form of the SDD concept be used; that is, instead of using the afternoon canopy–air temperature differential to develop the SDD parameter, one should use the midafternoon-presunrise canopy temperature differential, choosing some base value from which to calculate positive and negative values of SDD's.

If such a procedure is followed, an added complexity arises as a result of environmental variability that causes this essentially maximum-minimum canopy temperature differential to vary as a result of conditions not directly related to crop water stress. Idso *et al.* (*14*) have devised a means of reducing this complexity, but it requires air temperature

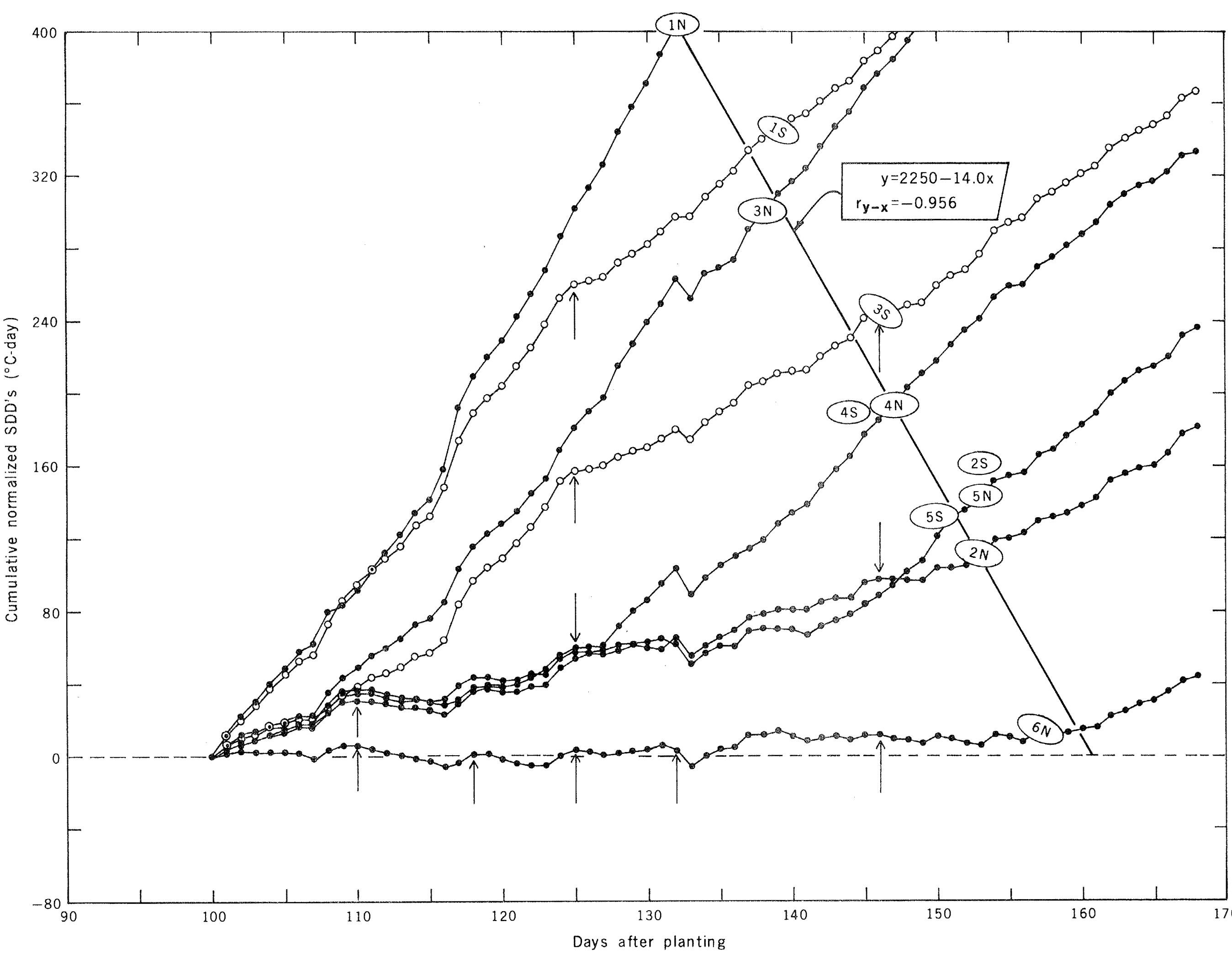
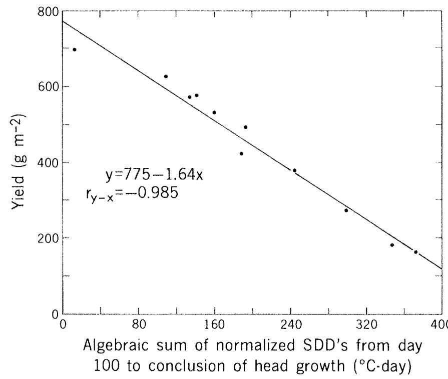


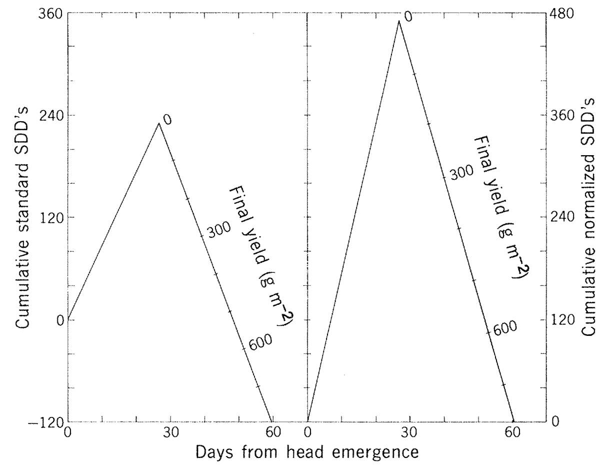
Fig. 5. Same as Fig. 3, except that the SDD parameter has been defined as

$$SDD_i = (T_{S,p.m.} - T_{S,a.m.})_i \left[\frac{18}{(T_{A,max} - T_{A,min})_i} \right] - 18$$

where $T_{S,p.m.}$ and $T_{S,a.m.}$ are, respectively, the midafternoon (about 2 p.m.) and early morning surface temperature measurements and $T_{A,max}$ and $T_{A,min}$ are, respectively, the daily maximum and minimum air temperatures.

Fig. 6 (left). Same as Fig. 4 with the difference noted for Fig. 5. Fig. 7 (right). Trifactor nomograms relating final grain yield to (i) the duration of time from head emergence to the cessation of head growth and (ii) the accumulation of SDD's over that period, as determined from combinations of the linear regression equations of Figs. 3 and 4 (left) and Figs. 5 and 6 (right). If a running accumulation of SDD's is plotted on one of these nomograms, plots similar to those of Figs. 3 and 5 will result, giving an indication of what final grain yields may be expected, based on temperature measurements to date and possible future weather scenarios or irrigation plans.





measurements near the times of both canopy temperature measurements. The saving grace in this approach is that these measurements need not be made over the crop but can be obtained from any standard temperature shelter within a few kilometers of the field site.

To illustrate these points, we have constructed Figs. 5 and 6 in analogous fashion to Figs. 3 and 4, respectively. We did this by normalizing all mid-afternoon-presunrise canopy temperature differentials obtained with the 20° f.o.v. downward-looking infrared thermometer to corresponding values for a day of standard environmental variability—arbitrarily defined as one whose maximum-minimum air temperature differential is 18°C—as per the method of Idso *et al.* (*14*). We then obtained the SDD parameter by using 18°C as the base value from which positive and negative deviations of normalized surface temperature differentials were calculated. The plotted results for air temperatures obtained over the crop canopy at the times of the canopy temperature measurements indicate that this approach is as good as both the previous forms of the SDD yield prediction technique. We also tested this approach with maximum and minimum air temperature data obtained from the National Weather Service Station at a distance of about 5 kilometers. Correlation coefficients corresponding to the linear relationships depicted in Figs. 5 and 6 were −0.960 and −0.967, respectively. Thus, all of these several approaches to predicting crop yield with the SDD technique appear to work equally well.

Generalizations

Let us now consider the implications of the general forms of our results by combining Figs. 3 and 4 and Figs. 5 and 6 to produce the trifactor nomograms of Fig. 7. Just how general are these graphs? To answer this question, we need to consider two major types of potential variability: the effects of differing temperature and water stress prior to head and awn emergence and the effects of different climatic regimes during the crucial period of head growth.

In the first instance, we hypothesize that soil moisture and temperature during the growth period prior to head emergence determine the potential range of yields that may ultimately be achieved as a result of subsequent variability in the period of head growth; that is, we postulate that the final grain yield lines of Fig. 7 will either expand or contract in scale in such a way that for more favorable conditions prior to the emergence of the head correspondingly greater final grain yields will be obtained, and vice versa, for a given set of conditions during the head growth period. The rationale for this hypothesis derives from the observation in Fig. 1 that the green leaf area index ceased to increase further once heads appeared at day 100. Thus, the maximum green leaf area index achieved by that time would seem to provide the potential for the head growth that follows. For a greater green leaf area index at the time of head appearance, we hypothesize a greater potential for subsequent head growth, that is, a contraction of the final grain yield scales of Fig. 7.

These hypotheses appear amenable to straightforward testing. In addition, they point to some further extensions of our prediction techniques. If the maximum green leaf area index achieved by the time of head emergence is indeed the determinant of final grain yield potential, we should be able to assess this potential remotely by means of albedo measurement (as implied by the data of Figs. 1b and 2 showing the variation in field albedo as the green leaf area index changes) and get an early estimate of final grain yield for different projected weather scenarios. Furthermore, from remote assessment of soil moisture availability and surface temperature at planting time and shortly thereafter, even earlier estimates of the maximum green leaf area index itself might be possible. Such would make possible construction of a whole hierarchy of procedures for final grain yield estimation that would progressively converge in accuracy as harvest time approached.

Summary

Our research efforts with durum wheat have led to the development of the SDD concept. Its application makes possible crop yield estimates from remotely acquired canopy temperatures and auxiliary air temperature measurements obtained during the period from head emergence to the cessation of head growth. Canopy albedo measurements appear adequate to delineate this critical period, making the technique potentially adaptable to predictions of crop yields by remote-sensing. The trifactor nomograms produced from combinations of the linear regression equations also suggest that the SDD concept may be used for scheduling irrigations by remote-sensing.

References and Notes

1. Office of Political Research, Central Intelligence Agency, "Potential implications of trends in world population, food production, and climate" (Library of Congress, Washington, D.C., 1976).
2. S. H. Schneider with L. E. Mesirow, *The Genesis Strategy* (Plenum, New York, 1976).
3. A. L. Hammond, *Science* **188**, 434 (1975).
4. W. Baier and G. W. Roberston, *Agric. Meteorol.* **5**, 17 (1968); H. A. Nix and E. A. Fitzpatrick, *ibid.* **6**, 321 (1969); E. A. Hiler and R. N. Clark, *Trans. ASAE* **14**, 757 (1971); L. M. Thompson, *J. Soil Water Conserv.* **17**, 149 (1962).
5. S. B. Idso, R. D. Jackson, R. J. Reginato, *Am. Sci.* **63**, 549 (1975).

6. S. B. Idso and R. D. Jackson, *J. Appl. Meteorol.* **8**, 168 (1969); ______, W. L. Ehrler, S. T. Mitchell, *Ecology* **50**, 899 (1969).
7. S. B. Idso and W. L. Ehrler, *Geophys. Res. Lett.* **3**, 23 (1976).
8. W. P. David, *Texas A & M Univ. Remote Sensing Center Tech. Rep. No. RSC-06* (1969); M. L. Horton, L. N. Namken, J. T. Ritchie, in *Evapotranspiration on the Great Plains* (publication 50, Kansas State University, Manhattan, 1970), pp. 301–338; V. I. Myers, M. D. Heilman, R. J. P. Lyon, L. N. Namken, D. Simonett, J. R. Thomas, C. L. Wiegand, J. T. Woolley, in *Remote Sensing with Special Reference to Agriculture and Forestry* (National Academy of Sciences, Washington, D.C., 1970), pp. 253–297; R. Karschon and L. Pinchas, *Oecol. Plant.* **6**, 43 (1971); A. R. Aston and C. H. M. van Bavel, *Agron. J.* **64**, 368 (1972); J. F. Bartholic, L. N. Namken, C. L. Wiegand, *ibid.*, p. 603; R. E. Carlson, D. N. Yarger, R. H. Shaw, *ibid.*, p. 224.
9. C. L. Wiegand and L. N. Namken, *Agron. J.* **58**, 582 (1966); W. L. Ehrler and C. H. M. van Bavel, *ibid.* **59**, 243 (1967); W. L. Ehrler, *ibid.* **65**, 404 (1973); B. L. Blad and N. J. Rosenberg, *ibid.* **68**, 635 (1976); T. Okuyama, *J. Agric. Meteorol.* **30**, 191 (1975).
10. "EarthSat spring wheat yield system test 1975 final report," EarthSat Corp. report 1052 prepared for the Johnson Space Center under contract NAS 9-14655 (National Aeronautics and Space Administration, Washington, D.C., 1976).
11. Trade names or company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.
12. S. B. Idso, R. D. Jackson, R. J. Reginato, B. A. Kimball, F. S. Nakayama, *J. Appl. Meteorol.* **14**, 109 (1975).
13. S. B. Idso and R. J. Reginato, in *Hydrology and Water Research in Arizona and the Southwest* (Univ. of Arizona Press, Tucson, 1974), vol. 4, p. 41.
14. S. B. Idso, R. D. Jackson, R. J. Reginato, *J. Appl. Meteorol.* **15**, 811 (1976).
15. Contribution from the Agricultural Research Service, U.S. Department of Agriculture.

The Distrust of Nuclear Power

Nuclear power is assessed hypercritically because of its unique history, complexity, and safety management.

Christoph Hohenemser, Roger Kasperson, Robert Kates

Nuclear power is in trouble. Despite the results of polls, which have shown repeatedly that the majority (about 60 percent) of the public view nuclear power favorably and think it safe (see Table 3), there is a sizable and growing opposition to nuclear technology. Public initiatives for a moratorium on nuclear development were recently defeated in California, Arizona, Colorado, Montana, Ohio, Oregon, and Washington. Nevertheless, similar initiatives are being prepared in another 19 states. Within the industry and in government regulatory agencies, there has been a significant defection of middle-level technologists (*1*). Many plants have been delayed or canceled, and capital costs will have risen from $300 per installed kilowatt in 1972 to an estimated $1120 by 1985 (*2*). The price of uranium tripled between 1974 and 1976, and the adequacy of the uranium supply after 1985 is in question (*3*).

All this is happening when many features of nuclear technology—low average pollution, cost advantages over coal- and oil-fueled plants in many areas, and replacement of foreign oil resources in electric power generation—should encourage rapid adoption of the technology. What causes the malaise?

Delays, cancellations, and rapidly increasing capital costs are not likely to be decisive in the long run. Recent delays and cancellations have been strongly affected by the decreased demand following the sudden doubling in electric energy prices in 1973 and 1974. Rapidly increasing capital costs are a function of the availability of capital, increases in labor costs, and the recent period of high inflation. These problems are shared by large new fossil-fired plants; solar plants would presumably have similar difficulties if they were available.

We attribute most of nuclear power's problems, therefore, to the issue of safety. For the last 2 years our interdisciplinary group has studied the safety issue, particularly to see how the risk of rare events enters into the energy policy decisions of our society. At first sight, the case for the safety of nuclear power reactors appears impressive. Some frequently cited statistics and examples are as follows.

1) The maximum permitted annual radiation exposure for persons living at the boundary of a nuclear power plant is 5 millirem. Routine population exposure from all nuclear power plants averages 0.003 millirem per person per year (*4*). In comparison, natural and medical sources contribute average exposures of 100 and 70 millirem per person per year (*4*, *5*), and individuals living in buildings constructed of volcanic rock (for example, in Rome) may be exposed to twice the natural background, or about 200 millirem per person per year (*5*).

2) When coal plants are located in large cities, the population exposure from radioactinides in fly ash is 500 man-rem per year (*6*); this exceeds permitted radiation exposures from reactors of equivalent power (*7*).

3) The most complete study to date of catastrophic reactor risk places the probability of a major radioactive release (release of an appreciable fraction of the volatile fission products found in the reactor core) at 1 in 100,000 reactor-years (*8*); of core meltdown at 1 in 20,000 reactor-years; and of a loss-of-cooling accident at 1 in 2000 reactor-years (*9*). These probabilities are given credence by the fact that to date, after 300 reactor-years of commercial reactor operation, there has never been a loss-of-cooling accident (*9*). With these probabilities, the expected number of prompt and delayed fatalities due to 100 reactors in the United States is only four per year; and the population exposed in the unlikely event of a major reactor accident would have a cancer risk only 1 percent greater than its preexposure risk (*9*).

4) Although plutonium is a potent carcinogen, substantial quantities ($\simeq 10^5$ kilograms) of it have been handled in the past 30 years with no apparent ill effects: there have been no cancers that can definitely be attributed to plutonium in the several thousand workers who have handled the material (*10*).

In early 1976 a committee of the National Academy of Sciences (NAS) began a study of the risks of various electric power technologies. While a detailed comparison is an extensive task and must await the NAS report, it is not difficult to characterize and compare the risks of the hydroelectric, coal, and nu-

---

Christoph Hohenemser is professor of physics and chairman of the program on science, technology, and society; Roger Kasperson is professor of geography and government; and Robert Kates is university professor and professor of geography at Clark University, Worcester, Massachusetts 01610.