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EXPERIMENTAL AIR EXCLUSION SYSTEM FOR FIELD STUDIES OF SO_2 EFFECTS ON CROP PRODUCTIVITY

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EXPERIMENTAL AIR EXCLUSION SYSTEM FOR FIELD STUDIES OF SO_2 AFFECTS OR CROP PRODUCTIVITY

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ABSTRACT

The objective of this project is to characterize and quantify the relationships among sulfur dioxide (SO_2) exposure, symptomatology of injury, and yield of crops that are economically important to the southeastern United States. Emphasis is placed on the soybean because of its sensitivity to SO_2 and its economic importance.

Five experimental sites--four in the vicinity of the Widows Creek Steam Plant and one at a location that receives exposure only to background levels of SO_2--were selected and characterized during the first year of study. Characterization includes analysis of soil fertility, pH, soil depth, slope, and content of organic matter. These data and data for the yield of soybeans were analyzed by regression methods to identify site factors that might affect yield and mask the effects of SO_2 exposure. Results of the soils analyses and regression analysis were used to adjust soil fertility and pH levels to optimal levels for soybean production and to eliminate a magnesium-potassium interaction that was affecting yield.

An air-exclusion system was designed, constructed, and tested that permits the comparison of plants exposed to SO_2 with plants at the same site that were protected from SO_2 exposure. The system, to remove or exclude SO_2-polluted air from 0.004-hectare plots during ground-level exposure, blows charcoal-filtered air through plastic tubes laid between rows of soybeans to remove the SO_2. This system is activated automatically when SO_2 concentrations in the vicinity of the plots equal or exceed 262 $\mu g/m^3$ (0.1 ppm). Tests showed the system to be as much as 85 percent efficient in excluding or reducing SO_2 concentrations to subthreshold levels during exposure. However, further testing is needed to improve system efficiency, particularly to protect plants less than 60 cm high from exposure. The soybean yields on plots exposed to SO_2 at one of the sites averaged 12 percent less than those on plots not exposed to SO_2. However, regression analyses of the data indicate that only about one-half of the reduction may be attributed to exposure to SO_2, the remainder being attributed to differences in other factors at that site.

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SECTION 1

INTRODUCTION

The toxicity of sulfur dioxide (SO_2) to plants has long been recognized and has been studied more intensively than that of any other atmospheric pollutant. Most research on the effects of SO_2 exposure on vegetation has been concentrated on the relationship between SO_2 dose (exposure time x concentration) and foliar injury that manifests itself as intercostal necrosis or chlorosis. Exposure to concentrations of SO_2 greater than 1045 $\mu g/m^3$ for an hour or more can cause visible foliar injury of sensitive vegetation (1). Some studies indicate that some species of vegetation can be exposed indefinitely to SO_2 concentrations less than 522 $\mu g/m^3$ without causing foliar injury (2,3). Mathematical equations have been developed that describe the relationship between the duration of exposure and the concentration of SO_2 that caused visible injury to various plant species. However, sensitivity to SO_2 does not depend on SO_2 dose alone; plants exhibit considerable variability in their sensitivity, depending on species, genetic and physiological characteristics of the individual plant, and the environment in which the plant is growing. Therefore, although equations are useful in predicting injury that might occur under given conditions for a limited number of species, these equations are not readily adaptable to assessing economic losses sustained by crops that have been exposed to SO_2 (4,5).

The influence of SO_2 dosages or foliar injury on plant productivity is less well documented or understood. Loss in productivity is relatively predictable in those cases in which reduction in foliage constitutes a direct loss in yield, as in the case of foliar SO_2 injury to forage crops such as alfalfa (3,6). However, there are few data on the indirect effects of foliar injury on seed or fruit production or growth. Linear relationships between total leaf area destroyed by SO_2 and reduction in yield have been reported for wheat (7), cotton (8), and soybeans (9) after exposure to SO_2 in closed chambers in the field where edaphic factors were held more or less constant. Using these data, regression models (i.e., $y = a + bx$, where y is percentage of full yield) were developed for estimating yield losses on the basis of measurements of a single independent variable such as total leaf area destroyed (x). Under normal field conditions, it is questionable whether yield losses resulting from foliar injury can be described by such a simple model because of the multiplicity of uncontrollable cultural, edaphic, and climatic factors that also affect yield. Jones et al. (10) were unable to detect a significant effect of foliar injury on yield of soybeans exposed to SO_2 emissions from a coal-fired power plant during the prebloom stage of growth. However, in a similar study, reductions in soybean yield as high as 351 kg/ha resulted from exposure to SO_2 emissions from the same power plant during the pod-filling stage of growth (11). The reductions in yield were found to be related to the amount of foliar chlorosis. In general, crop yields are not affected by exposure to SO_2 unless visual foliar effects occur, and apparently, more than five percent of the leaf area must be destroyed to measurably reduce yield. Experiments with alfalfa indicate that, if leaf destruction is less than five percent, no residual effect on yield will occur, even after several exposures (4).

Most documented cases of SO_2 exposures that occurred under field conditions and caused permanent adverse effects on the growth or yield of vegetation have been associated with emissions from smelters. The effects were caused by relatively high frequency of exposure to excessive concentrations of SO_2. This type of exposure does not occur normally in the vicinity of modern, well-sited coal-fired power plants that are equipped with tall stacks (5). No evidence has been presented to show that emissions from such plants have caused reductions in plant productivity. The only report, for the United States, of power plant emissions affecting the productivity of a seed crop is that of Jones et al. (11) for the Shawnee Steam Plant in western Kentucky, which at the time of the exposure was equipped with short stacks.

Foliar injury can occur in crop and forest species when they are exposed to SO_2 dosages that do not exceed the national secondary ambient air quality standard of 1306 $\mu g/m^3$ for 3 h (1). However, there are insufficient data to predict (1) the amount of foliar injury that may occur for exposure at or below the standard or (2) whether such exposures affect productivity (12). Furthermore, the SO_2 may interact with other pollutants, such as fluorides and oxides of nitrogen, that are emitted from coal-fired power plants or with oxidants in the ambient air to produce effects on vegetation.

Development of a capability for assessing the direct impacts of atmospheric emissions of SO_2 from coal-fired power plants will require characterization of dose-response relationships among SO_2 dosages (alone and in mixtures of other pollutants), occurrence of foliar injury, and effects on productivity under controlled exposure conditions. Emphasis should be placed on (1) dosages that are near and within the secondary standard for SO_2 and (2) species such as soybeans that are especially sensitive to SO_2 and, at the same time, economically or ecologically important. Of equal importance are (1) documentation of the occurrence of both short- and long-term effects of ambient SO_2 levels on the productivity of vegetation and (2) validation of dose-response relationships obtained under controlled exposure in the field. The principal obstacle to characterization and quantification of SO_2 effects in the ambient environment is the selection of adequate controls or baselines for making valid comparisons of productivity between exposed and unexposed vegetation; that is, the difficulty is to isolate an effect caused by SO_2 exposure from one caused by other factors in the environment that are difficult to control or identify. In general, three types of approaches were used to isolate SO_2 effects in the field:

1. Effects on plants grown in experimental plots were compared at increasing distances from an SO_2 source, or effects at plots near the source were compared with those at a location remote from sources of the type being investigated. Plots close to the source experience a higher frequency of exposure and a higher dosage than plots at increasing distance from the source. To make valid comparisons, all other factors affecting growth must be constant or equalized, a task which is difficult and sometimes impossible to achieve.

2. Effects on plants grown in containers were compared at increasing distances from the emission source. In this approach, most edaphic factors are held constant, but climatic factors cannot be controlled. This approach is impractical if the plants are to be grown to maturity because restricted root growth may affect normal growth and development.

3. Effects on plants grown in field chambers that are ventilated with charcoal-filtered air are compared with effects on plants grown in chambers ventilated with ambient air. This approach is the most promising because exposed and unexposed plants can be compared at the same location, minimizing the effects of differing site factors. However, the use of field chambers has resulted in special problems.

Mandl et al. (13) summarized the development and use of field exposure chambers since 1896. All field chambers used until 1971 were of a completely closed design. In a closed system, filtered and unfiltered ambient air is circulated through paired chambers and vented under positive pressure to the atmosphere. Because of the closed design and the characteristics of the covering material, radiant heat is trapped, necessitating constant air circulation. This air circulation causes abnormal air movement around foliar surfaces and changes the water economy of plants. Exposure to natural precipitation and plant pests, which causes problems in field plots, is precluded.

As a partial solution to these problems, Mandl et al. (13) designed and tested a field chamber with an open top. This chamber design essentially eliminates heat buildup within the chamber, admits sunlight and natural precipitation, and prevents infestation with insects and disease that occurs in field plots. However, continuous air circulation is still required, and a pair of chambers (one with filtered air circulation and one with ambient air circulation) is needed for each replication.

Howell (14) compared yields of soybeans grown in paired, open-top chambers with yields in field plots. Significant reduction in soybean yields occurred in the plants grown in chambers ventilated with ambient air as compared with those grown in chambers with filtered air or those grown in the field plots. There was no difference in yields between the filtered air chambers and the field plots. Howell concluded that, under the conditions of his experiments, field chambers in some way increased the sensitivity of soybeans to pollution.

TVA biologists used all three approaches to determine the impact of stack emissions from coal-fired power plants on the appearance, growth, and yield of soybeans. Soybeans were selected for study because of their high sensitivity to SO_2 and their economic importance to the Tennessee Valley region. Three specific types of experiments were conducted:

1. Soybeans were grown in portable greenhouses that were partitioned into two equal sections, with one section receiving filtered air and the other receiving ambient air. The greenhouses were located about 3 km from the steam plant in an area receiving a relatively high frequency of exposure to high SO_2 concentrations.

2. Soybeans were grown in six field plots located 3.5 to 56.5 km from the steam plant. All plots were located in the same type of soil and were fertilized and limed to the same levels.

3. Soybeans were grown in 19 small (3- by 3-m) field plots located 3.2 to 43.8 km from the steam plant. To minimize edaphic differences among sites, plants were grown at each location in four 30-quart styrofoam chests containing a standard soil mixture. Rainfall was supplemented with irrigation so that all plots received essentially the same weekly ration of water.

During the five years of operation of the filtered and unfiltered greenhouses, the soybean yields have averaged 24 percent less in the unfiltered portion of the greenhouse than in the filtered portion. Because the plants grown in the filtered section are protected from contaminants from all existing sources, TVA biologists cannot conclude that the steam plant emissions were the sole cause of the reductions in yield in the unfiltered sections. Also, because continuous air circulation is required to prevent excessive temperatures, plants must be irrigated to offset evapotranspiration losses. The irrigation tends to produce luxuriant growth, and yields have been considerably above those of field-grown plants. Comparisons between yields of crops grown under optimum growing conditions and yields of those grown under field conditions must, therefore, be interpreted with caution. No significant differences were detected between the growth and yields of soybeans grown near the steam plant in areas receiving exposure to SO_2 and the growth and yields of soybeans grown at remote locations. However, there was considerable variability, possibly because of edaphic and climatic factors, in yields within sites and between sites. In general, plots near the steam plant tended to produce higher yields.

To overcome the problems associated with field chambers and with field plots in different locations, a prototype air-exclusion system was designed and installed in 1975. The system (see Materials and Methods) eliminates the need for an enclosure and, therefore, the need for continuous air circulation. Filtered air is circulated through the plant canopy only when the pollutant concentration reaches a predetermined concentration. Because the system operates for only a small part of the time, a parallel system for control is unnecessary. Results of this preliminary test showed that the yield of soybeans (c. v. Forrest) was 28.6 percent lower in the plot without the air-exclusion system. The yield from the air-exclusion plot was comparable to yields normally expected under field conditions, but was less than half the yields obtained in the greenhouses. However, the percentage reduction in yield between greenhouse treatments was the same as that observed for the air-exclusion study. As a result of the successful test with the 1975 prototype, plans were developed to expand the study. It was proposed that 30 air-exclusion units be constructed, installed, and evaluated on five sites in 1976.

This report describes the air-exclusion system, its operation, and evaluation of its efficiency at excluding pollutants from the crop; the establishment and characterization of the study sites; and the results obtained for the 1976 growing season.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Experimental plots (Figure 1) were established at four sites on Sand Mountain near the Widows Creek Steam Plant in northeast Alabama and at a remote location at the Auburn University's Sand Mountain Experiment Station to study the effects of SO_2 emissions from the steam plant on crop productivity. A system was designed and constructed to blow air that has been filtered by charcoal to remove SO_2 through plastic tubes to exclude SO_2-polluted air from experimental plots during ground-level exposures. The air-exclusion system is activated by a continuous SO_2 monitor when the monitor registers SO_2 concentrations of 262 $\mu g/m^3$ or more. Three air-exclusion systems were installed on soybean plots at each site to compare the yields of plots protected from SO_2 exposure by the systems with those of plots that were not protected. The primary objectives of the first year of investigation were (1) to identify the sources and magnitude of variation within sites and between sites attributable to factors, primarily edaphic, that might mask SO_2 effects so that measures could be taken to minimize them and (2) to characterize the efficiency of the air-exclusion system in protecting vegetation from exposure to SO_2. The secondary objective was to measure the effect of SO_2 exposure in terms of foliar injury and productivity of soybeans. Soybean plants are extremely sensitive to SO_2 and are a crop of great economic importance in the Southeast. Several years might be required to obtain sufficient data for characterization of the effects of SO_2 on the productivity of soybeans grown under ambient conditions.

CHARACTERIZATION OF SITE FACTORS

Analyses of the surface and subsurface characteristics of the sites showed that soil depth was extremely variable at site 19. Because the growth and yield of plots at site 19 reflected the shallowness of soils in some areas, site 19 was abandoned at the end of the growing season and a new site was established. Some shallow spots that were identified at site 6 will not be used for plot locations in the future. No effect of soil depth on yield was detected by regression analyses for sites 6, 10, 9, and 22. Measurements of slope identified areas requiring drainage to minimize excessive soil moisture at some sites during periods of high rainfall.

Soil analyses showed that the phosphorus (P) and magnesium (Mg) contents and pH of the soil varied within plots at site 6 and that Mg and pH varied at site 10. Furthermore, levels of P, Mg, and calcium (Ca), percent organic matter, and pH varied considerably among sites. Regression analyses were used to identify soil factors that influenced yields among the experimental plots and that might mask the effect of SO_2 exposure on yields; most significant was a magnesium-potassium (Mg-K) interaction. Increased yields were associated with increasing ratios of Mg to K. Levels of Mg were

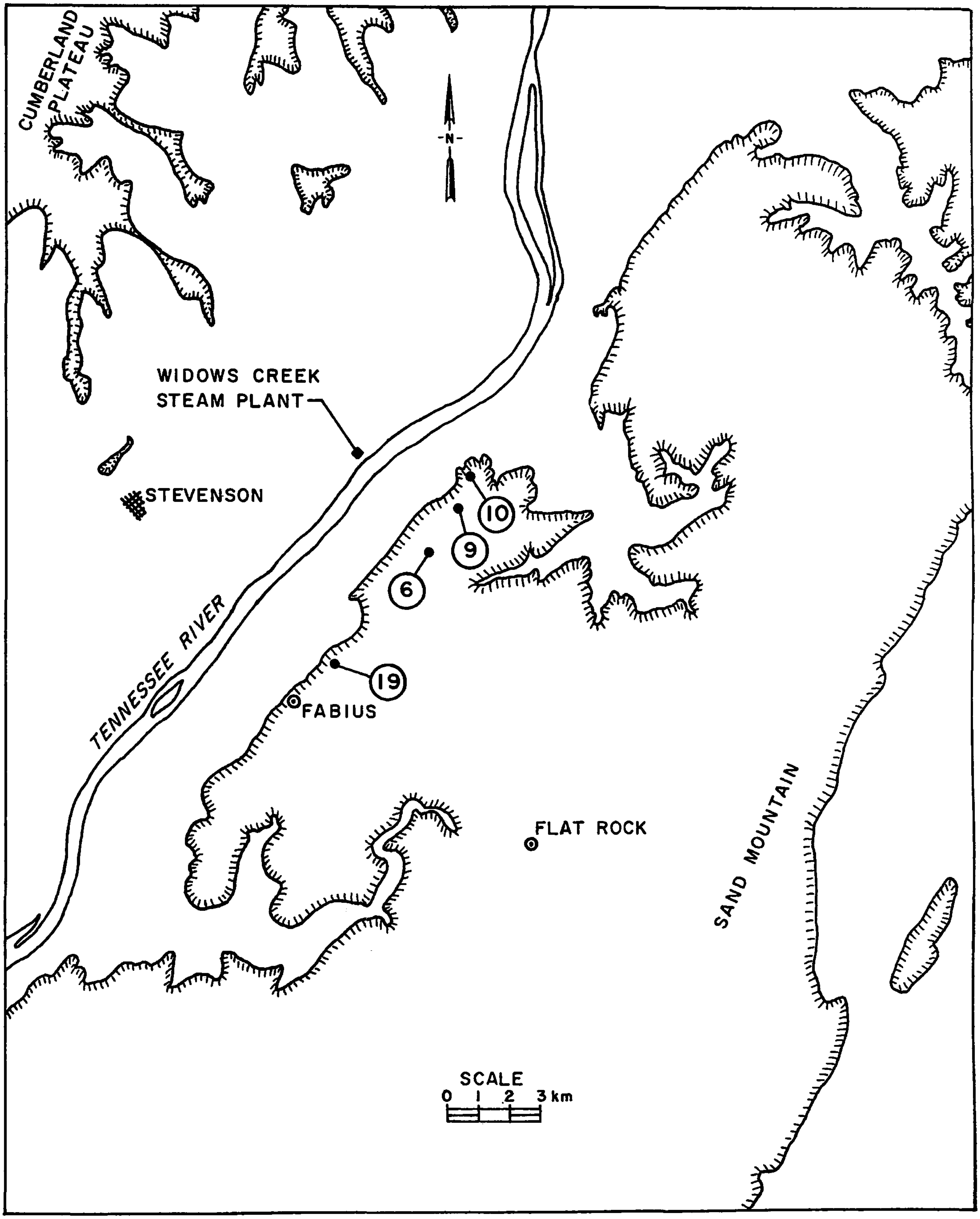

Figure 1. Location of continuous SO_2 monitors and associated study sites near Widows Creek Steam Plant.

optimized at all sites by the addition of dolomitic lime or magnesium sulfate, depending on whether there was also a need to optimize pH levels. Levels of P at site 9 tended to be excessive, and regression analyses indicated that yields might be reduced at the higher levels. However, levels of P were uniform among the plots on the site and, therefore, should not affect comparisons of treatments at the site.

Content of organic matter in the soil was an important variable in explaining variation in yields among the sites. However, percent organic matter is relatively uniform among plots within sites and should not affect comparisons of treatments. Regression analyses also identified strong interactions among percent organic matter, pH, and Ca, with greater amounts of Ca being required to produce the same pH in soils with high organic content as in those with lower organic content.

EFFICIENCY OF AIR-EXCLUSION SYSTEM

Smoke, fog, and SO_2 exposure tests indicated that the air-exclusion system might be as much as 85 percent efficient in excluding or removing SO_2 from the soybean plots after the plants are about 2 feet tall. The system was least efficient during the seedling stage of growth. Any SO_2 that was not removed from the plots was reduced to concentrations below the 1000- to 1300-$\mu g/m^3$ level generally required to cause threshold injury to most sensitive species of vegetation. Comparisons of observations of chlorosis and measurements of foliar sulfur between plots with air-exclusion systems and those without indicated that the exclusion systems effectively reduced both chlorosis caused by SO_2 and accumulation of sulfur on foliage. After an SO_2 exposure at site 6, exposed plots averaged 6.4 percent chlorosis whereas the air-exclusion plots averaged 0.9 percent chlorosis. The sulfur content of the foliage at the exposed plots was 34 percent higher than that at the air-exclusion plots.

Results of the tests suggest that further testing is needed to complete characterization of the efficiency of the air-exclusion system and that the efficiency of the system could be improved by preventing air loss from the periphery of the plots below the plant canopy. Studies are planned for 1977 in which artificial SO_2 exposures will be used to evaluate the effect of placing air barriers around the periphery of the plots to increase the efficiency of the system over the life cycle of soybeans. In addition, SO_2 will be monitored continuously within the plots over the growing season to evaluate the system under ambient conditions.

SO_2 EFFECTS ON SOYBEANS

Exposure to concentrations of about 1500 $\mu g/m^3$ (0.6 ppm) SO_2 maximum 1-h average and 1100 $\mu g/m^3$ (0.4 ppm) SO_2 maximum 3-h average was required for visible threshold injury to the foliage of soybeans. Exposure to concentrations of about 2350 $\mu g/m^3$ (0.9 ppm) SO_2 maximum

1-h average and 1500 $\mu g/m^3$ (0.6 ppm) SO_2 maximum 3-h average was required for significant injury (>5 percent leaf area affected). The response of soybeans to these concentrations would be expected to vary somewhat, depending on environmental conditions before, during, and after an exposure and the variety and physiological condition of the individual plants. However, other data for the relationship between SO_2 concentrations and the occurrence of foliar effects on soybeans in the field generally agree with these determinations.

Of the three sites on Sand Mountain, site 6 exhibited the most evidence of yield reduction due to SO_2. Site 6 experienced the greatest frequency of exposure to high concentrations of SO_2 at ground level ($\geq$1300 $\mu g/m^3$) and was the only site at which exposed plots exhibited significant foliar injury. At site 6 the exposed plots had significantly greater amounts of foliar sulfur. The difference in yields between protected and exposed plots at this site averaged about 402 kg/ha. However, a local regression model attributed 222 kg/ha of the difference to SO_2 exposure and the rest to differences in other factors at site 6. Thus, although not conclusive, the data indicate that a reduction in yield of about 6 percent was attributable to SO_2 exposure at site 6. Air-exclusion plots at all the other sites produced somewhat greater yields than their comparable controls.

The residuals (unexplained variation) for yields generated by the local model suggest that strong positive or negative bias might exist for plots within treatments at some of the sites as the result of unidentified site factors. Therefore, the residuals were used to relocate those plots that will be used next year within treatments at each site to reduce the chance that these factors might bias treatment in a single direction and result in a misinterpretation of the effect of SO_2 exposure on yields.

SECTION 3

MATERIALS AND METHODS

SELECTION AND LOCATION OF STUDY SITES

The study area is located on Sand Mountain in Jackson County in northeast Alabama, about 48 km southwest of Chattanooga, Tennessee, in the proximity of the Widows Creek Steam Plant. The steam plant is the third largest coal-fired electric-generating facility in the TVA system and has a rated generating capacity of about 1971 megawatts (MW). It consists of six 141-MW units, one 575-MW unit, and one 550-MW unit. Stack heights are 48 m for the six small units and 152 m for the two larger units. The steam plant is located on the Valley floor, about 183 m above sea level. The study area on Sand Mountain is about 3 km east of the plant at an elevation of 457 m above sea level. A control site for the project was installed at Auburn University's Sand Mountain Experiment Station at Crossville, DeKalb County, Alabama, about 69 km southwest of the steam plant.

The Widows Creek area was selected for this study for the following reasons:

1. The relatively high frequency of occurrence of ground-level SO_2 exposures in the area. This phenomenon results from a combination of the short stacks, topography, and prevailing meteorological conditions. Dispersion of pollutants is restricted by the Sand Mountain Plateau, located 1.6 km east of the steam plant, and the Cumberland Plateau, located 8 km northwest of the steam plant. Adverse meteorological conditions are associated with a midmorning shift in airflow from a down-valley to an up-valley direction, a situation that frequently carries the plume across the Sand Mountain Plateau. Because of the proximity of the Sand Mountain Plateau to the steam plant, persistent ground-level exposures may occur before adequate dispersion has taken place.

2. The availability of existing continuous SO_2 monitors and meteorological stations in the area.

3. The availability of agricultural land for establishment of experimental sites adjacent to SO_2 monitors.

4. The importance of agriculture and forestry to the area.

The air monitoring network at the Widows Creek Steam Plant consists of 14 stations at which SO_2 is monitored. These stations were located in this area because of the probability of frequent exposures by SO_2 based on dispersion models and field observations of vegetation affected by SO_2. Sites at monitoring stations 6, 9, 10, and 19 (Figure 1) were selected as experimental study areas because research plots had previously been located there and additional land was available for lease.

A Philips SO_2 monitor was installed at the control site at Auburn University's Sand Mountain Experiment Station to verify that only background-level SO_2 exposures occur at the site.

Parcels of land adjacent to the monitors, each about 0.4 hectare (ha) in size, were leased from their owners. The sites differ in configuration because of terrain limitations or inability to lease better sites. Sites are referred to by monitor numbers. Each site was subdivided into twenty-four 0.004-ha plots--12 for air-exclusion plots and 12 for exposure to ambient air. The arrangement of plots at each site and the direction from the steam plant are shown in the figures in appendix A. Air-exclusion and exposed plots cropped in 1976 are also shown in these figures.

CHARACTERIZATION OF EDAPHIC FACTORS

Soil Description

The soils at all monitors except monitor 19 are of the Hartsells series. Monitor 19 is of the Hanceville series. A complete description of the soil characteristics, productivity, average seasonal precipitation levels, and average temperature is given in appendix B.

Soil pH and Fertility

Soils were sampled before planting and were analyzed for P, K, Ca, Mg, and pH by the Soils Testing Laboratory at Auburn University, Auburn, Alabama. The sulfur content was determined by the Leco sulfur analysis method (15).

An attempt was made to optimize the pH and fertility of the plots by adding 4.5 metric tons of dolomitic lime and 1.1 metric tons of 4-24-24 NPK fertilizer per hectare in the spring of 1972 as soon as soil conditions permitted.

The soils were sampled again after harvest in 1976 and were analyzed for content of organic matter and the variables listed above. These data were used to adjust soil fertility and pH levels for 1977 studies and in regression analyses to account for variations in soybean yields among the experimental plots. (For results of the soil analyses, see appendix C.)

Depth to Bedrock

The soils on Sand Mountain, although used extensively for truck farming, are relatively shallow and, therefore, subject to drought during periods of low rainfall. Depth to bedrock at individual plots was measured to identify subsurface characteristics that may affect plant growth and development.

Three measurements per plot were made with a 90-cm soil auger. One measurement was made at the center of the plots, and the other two measurements were made at the front and rear of the plots. (The front of the plot is identified by the location of the plot number stake.) Points between plots were interpolated to obtain a complete rectangular array of data for each site. An interactive three-dimensional graphics computer routine was used to depict the subsurface characteristics.

The terrain at each site was characterized to determine whether slope or low-lying areas where surface runoff could accumulate affected growth, development, and symptom expression of plants. Characterization of the surface was accomplished by measuring with a transit and rod the relative elevation of each plot on a 6- by 6-m grid. A temporary benchmark was established at each site to determine the height of the instrument for future reference. An interactive three-dimensional graphics computer routine was used to depict surface characteristics. The slope of the plots was determined by difference in elevation from front to rear of the plots.

AIR-EXCLUSION SYSTEM

Description

The air-exclusion system is a type of field exposure facility that consists of three modules: air filtration, air circulation, and air distribution.

The air filtration module consists of a dust filter and six panels, each containing about 4.3 kg of charcoal in a galvanized metal box. The box is airtight, except for the inlet blower, and is attached to the air circulating module. The charcoal is of the activated CH type.[1] Access to the filters is through a hinged lid that, in the closed position, is sealed to the box with a gasket.

The filter module containing the dust filter and charcoal filter panels is shown in Figure 2.

The air circulating module consists of a wheel blower with a rated air delivery of 122 m^3/min. The blower is powered by a 1.5-hp motor energized by 220 V a.c. The blower and the filter box are mounted on an angle iron frame.

The air distribution module consists of two components: an exhaust duct and four plastic tubes. The exhaust duct is constructed of galvanized sheet metal and contains fins and deflectors to distribute the airflow evenly into four exhaust ports (Figure 3). Krene plastic tubes, attached to the posts, extend between the rows of the crops. The dimension of the tubes, hole size, and distribution are shown in Figure 4.

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1. All equipment and vendors are listed in appendix D.

Figure 2. Filter module containing dust filter and charcoal filter panels.

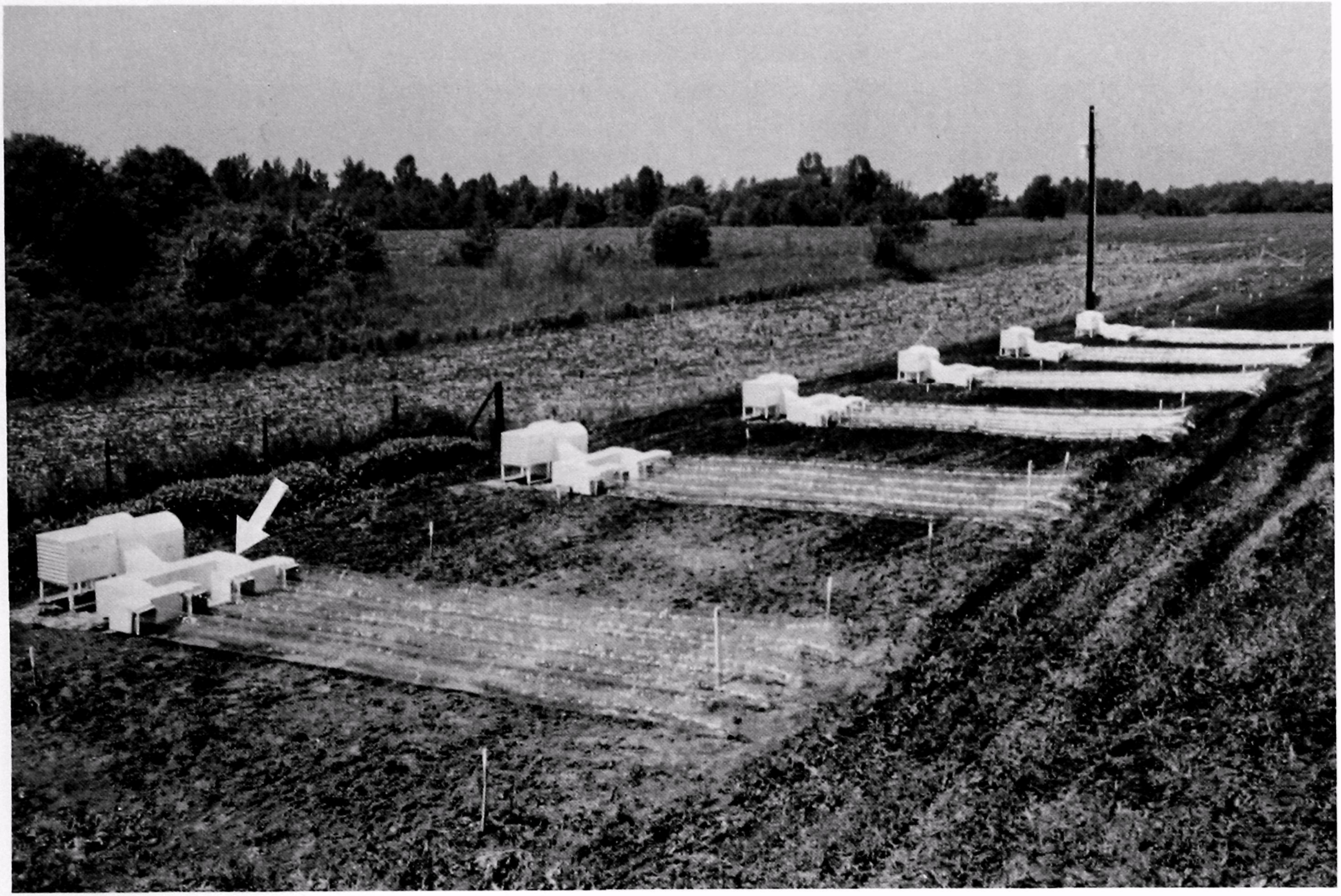

Figure 3. Air-exclusion units at monitor 6 showing charcoal filter box and blower assembly, exhaust duct (arrow), and krene plastic tubes.

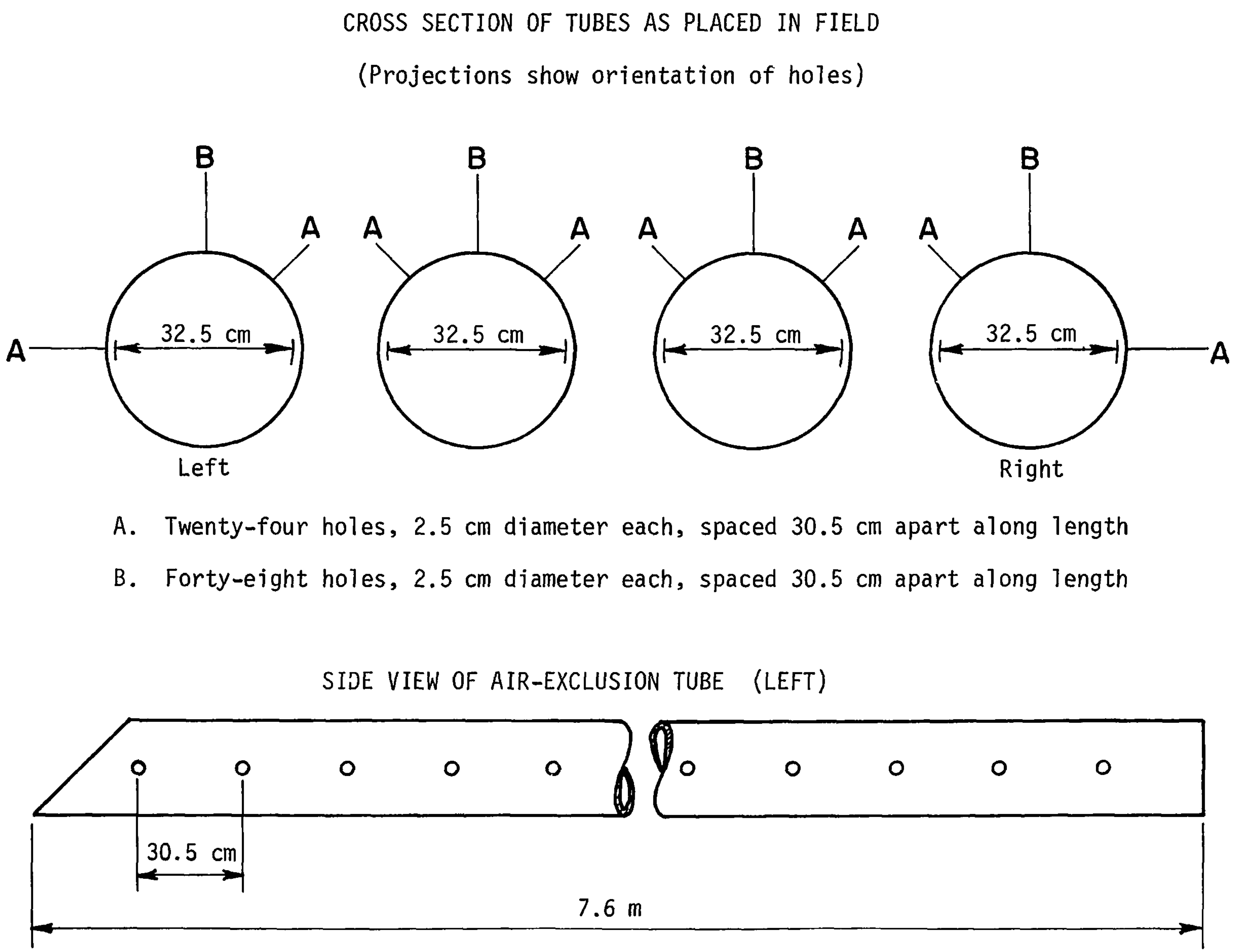

Figure 4. Krene plastic tubes for air-exclusion system.

Installation and Operation

The air-exclusion units were installed on patio blocks and wired through underground service lines to a central breaker panel. A relay in the SO_2 recorder activates the air-exclusion units when the SO_2 concentration reaches 262.0 $\mu g/m^3$. The units were installed during the first three weeks in May 1976 and put into operation when the seedlings emerged from the ground during the first week in June.

A digital timer was wired into the SO_2 recorder relay that activates the blowers to record the number of hours of operation. The timers were read and reset each week. An average time of operation was compiled each week, and the blowers at monitor 22 were operated an equal period during each following week. The latter operation was controlled through a timer switch. The blowers at Crossville were operated for an amount of time equal to the average operating time of blowers at the Widows Creek site to determine whether blowing air through the crop affects growth and yield of the crop.

The efficiency of the charcoal filters was determined by passing SO_2 from a permeation tube through a known quantity (1 g) of charcoal inserted in the sampling train of an SO_2 monitor. The amount of SO_2 adsorbed by the charcoal was calculated by measuring the flow through the monitor. Estimating the average SO_2 concentration in the Widows Creek area would allow calculation of the amount of time that the air-exclusion units could operate efficiently to remove SO_2. As a check to the above method, the actual SO_2 exposures that were recorded by the monitors at the experimental site during the 1976 growing season were calculated to determine whether the SO_2 burden exceeded capacity for SO_2 adsorption of the charcoal charge of the air-exclusion units.

Testing Efficiency

Extensive tests were conducted during the summer of 1976 to evaluate the efficiency of the air-exclusion system for excluding air pollutants. Five types of tests were used: smoke grenades, fog generation, artificial SO_2 exposure, sulfation plates, and foliar sulfur analysis.

Smoke Tests--

Tests were performed with 3-min smoke grenades immediately after the system was installed and before the seedlings emerged from the ground. The first test was conducted on June 2 between 5:45 a.m. and 6:20 a.m. Wind speed during the test was 0.5 to 1.5 m/s. Observations were recorded with a still camera.

Fog Generator Tests--

The second test was conducted with a fog generator July 21 between 7:30 a.m. and 10:30 a.m. The soybeans averaged 66 cm in height. Wind speed during the tests averaged 2 m/s. Observations were recorded with a still camera and a movie camera.

SO_2 Exposure Tests--

The third test was conducted by artificial SO_2 exposure on September 11 between 10 a.m. and 2 p.m. The average height of the soybeans was 102 cm. During this test, the plot was enclosed with a 60-cm-high fiberglass air barrier. The air barrier around the periphery of the plot was placed to reduce lateral air loss from the side of the plot and increase vertical air movement. Two portable SO_2 monitors were placed inside the plot. A third monitor equipped with a 4.5-m sampling probe was placed outside the plot, and samples were drawn from various locations within the plot. Wind speed during the test averaged 1.5 m/s. Anhydrous SO_2 was injected into a 5-cm plastic pipe that had been perforated along one side to simulate a line source of SO_2. The SO_2 was diluted by forcing air into the pipe with a squirrel cage blower.

The fourth test also consisted of an artificial SO_2 exposure conducted October 8 between 9 a.m. and 12 p.m. Wind speed during the test averaged 0.6 m/s. This test was performed on a cotton plot because the soybeans were defoliated. The plot was enclosed with a 30-cm-high fiberglass barrier between the inner and outer buffer rows.[2] One portable SO_2 monitor was placed in the center of the plot, and the monitor with the 4.5-m probe was used again as in the previous test. This test was performed in two parts. The first part of the test was conducted to determine whether reducing the plot size by placing the barrier between the buffer rows would increase vertical airflow. The second part of the test consisted of reducing by half the length of plastic tubes and reducing the plot size by half its original length, thereby doubling the airflow through the plot.

Sulfation (Huey) Plate Tests--

Sulfation plates were used to quantify the efficiency of the air-exclusion system in excluding SO_2 from the plots (16). Plates were installed at monitor 9 on three air-exclusion plots and on two exposed plots. Plates were set in the center of each plot at 30 and 60 cm above ground on July 15 and at 120 cm above ground on August 5. Plates were changed monthly and analyzed by the turbidimetric barium sulfate method (17). All plates were removed October 8 when the air-exclusion system was deactivated.

Foliar Sulfur Analysis--

Soybean foliage was analyzed for total sulfur content at the end of the growing season in another attempt to quantify the efficiency of the air-exclusion system. Samples of soybean foliage were collected

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2. Buffer rows and buffer plants are rows of plants or additional plants around the periphery of an experimental area to reduce the edge effect on the test plants. Plants on the periphery of a plot are exposed to more sunlight than plants grown in the interior of the plot, thus resulting in an edge effect.

from all sites on September 28 and 29 according to the following procedure: Five soybean plants from the inner buffer rows were harvested, placed in paper bags, and transported to Muscle Shoals. The following day the five topmost trifoliates from each plant were cut, excluding the petioles, and washed in a mild soap solution, rinsed with running tap water, and rerinsed with distilled water. The leaves were dried at 70°C for 24 h in a forced-draft oven. The dried leaves were ground in a Wiley mill and analyzed by the Leco sulfur analysis method (15).

CULTURAL PRACTICES ON EXPERIMENTAL SITES

Soil Treatment and Plot Establishment

The experimental sites were plowed and disked in the spring of 1976 as soon as field conditions permitted. The sites were then limed, fertilized, and disked again. Plots were staked (appendix A), and electrical service lines were installed underground.

Two weeks before planting, Trifluralin was applied at the rate of 0.126 cm^3/m^2 and tilled to a depth of 7 to 10 cm immediately following application to control weed growth.

Planting

Soybean [*Glycine max* (L.) Merr. c.v. Essex] was selected as a test crop because of its growing importance in the agricultural economy of the Widows Creek area, the Tennessee Valley, and the Nation. The Essex variety was chosen because of its maturity grouping and nonbranching habit. Seed were obtained from the Auburn University Sand Mountain Experiment Station, treated with a commercial preparation of Captan and molybdenum, and inoculated with *Rhizobium bacterium*. Seed were planted by hand in furrows at the rate of 1 to 2 seed every 5 to 7 cm. Seven rows, 7.3 m long, were planted 75 cm apart on each plot. The two outer rows on each side of the plots served as buffer rows, and the plants in a 0.61-m length at each end of the three inner sampling rows served as buffer plants for the row. The sampling rows were divided into 10 sections 0.61 m in length, staked, and numbered to provide permanent identification of the section. Planting dates are presented in appendix E.

Air-Exclusion Treatment

The locations of the soybean plots at each monitor are shown in appendix A. Each site had three air-exclusion plots (test plots) and three exposed plots. The exposed plots had plastic strips between the sampling rows to simulate the mulching effect of the plastic tubes of the air-exclusion system. Three additional soybean plots were installed without the plastic strips at monitors 6, 9, and 10 to determine whether plastic mulching had an effect on growth and yield.

Weed and Pest Control

The plots were kept free of weeds throughout the growing season by hand weeding and hoeing. Pests were controlled as necessary. Soybeans were sprayed biweekly with either Malathion or a broad-spectrum insecticide containing Carbaryl, Meta-Systox, and Kelthane to control the Mexican bean beetles, stink bugs, and grasshoppers. Sprays were applied with either a backpack sprayer or a high-pressure orchard sprayer, according to recommendations of the manufacturers.

Seed Harvest and Processing

Soybeans were threshed by row (including the two inner buffer rows) in the field with a plot thresher. Considerable differences existed between and within sites in reaching harvest maturity. Harvesting dates are presented in appendix E.

Beans were cleaned by hand to remove soil particles and plant debris. The bean samples were subsequently dried in a forced-draft oven at 70°C to constant weight, placed in a desiccator to cool, and then weighed.

Bean size was determined by weighing 10 replicate samples of 100 beans from each of the sampling rows.

ENVIRONMENTAL MONITORING AND OBSERVATIONS

SO_2 was measured continuously at each site with a Philips SO_2 monitor. O_3 was measured at monitor 9 with a chemiluminescent O_3 monitor from June 22 to September 21 to determine whether its concentration was of sufficient intensity to cause injury or synergistic effects. Temperature and relative humidity were measured with hygrothermographs at monitors 6, 9, and 19 and at the TVA mountain meteorology station in the vicinity of monitor 9. Solar radiation was measured at the TVA meteorology station located about 1.6 km south of the Widows Creek Steam Plant. Temperature, relative humidity, and solar radiation were measured because of their influence on the sensitivity of plants to SO_2. Precipitation gauges were installed at all sites except site 22 to record precipitation; precipitation measurements from the Sand Mountain Experiment Substation were used for site 22. These measurements were made to determine differences in moisture levels among sites and as an indicator of moisture stress.

PLANT OBSERVATIONS

Measurements of plant growth, development, symptom expression, and incidence of insect activity and plant diseases were made each week beginning the first week in July and ending the second week in September. Weekly observations were made to compare visible SO_2 injury with various stages of plant development, subsequent reductions in yield, if any occurred, and SO_2 exposures.

Observations were taken according to the following procedure. Two sections, 0.61 m long, from each of the three inner rows in each soybean plot were used as observation points every week. One section was randomly selected at the beginning of the growing season and was constant for the remainder of the growing season. The second section was randomly selected each week. Observations were made by trained individuals on a rotation basis. A team of two individuals made observations each week, with one member of each team having been a member of the team of the previous week. This procedure provided continuity in observation from week to week.

ANALYSIS OF DATA

Data for this study were analyzed by one-way analysis of variance (ANOVA); the stepwise regression procedure; scatter plots of measured and estimated variables; correlation coefficients; and multiple regression analysis, including least-squares and "robust" regression. The analyses were performed with two interactive computer packages of statistical procedures, the Statistical Analysis System (SAS76) (18) and MIT-SNAP (19).

Differences in factors that might confirm the presence of SO_2 in the plots (percentage foliar chlorosis, percentage total foliar sulfur) and factors that ultimately might be the mechanism for yield reduction caused by SO_2 (final plant height, bean weight) were compared using ANOVA. Yield differences among treatments also were tested in this manner. To determine the effect of SO_2 on yield using ANOVA, all other variables affecting yield must be controlled. Since this was not the case, further analyses were necessary to isolate the effect of SO_2 on yield. To accomplish this, regression analysis was used to obtain a model expressing the size of the effect of any limiting variables, including SO_2, on yield. Because of the number of factors that might influence the outcome of a large field experiment of this type, it was necessary to identify which factors were most important among all the factors for which data were available in describing the outcome and use of these variables in regression.

Several techniques were used to identify these variables. The stepwise regression procedure from SAS76, which is capable of selecting a model containing a combination of variables from a large group of independent variables, was used to provide a basis for selecting variables to be used in multiple regression. Scatter plots were generated by MIT-SNAP to permit examination of the relationship between the measured and estimated variables. These plots were useful in identifying variables influencing yield; variables that should be transformed to provide a better fit in the regression analysis; and interactions between independent variables. Correlation coefficients obtained from SAS76 provided additional information on which variables were most highly associated with yield and on the degree of interaction of any of the independent variables. The variables selected from the techniques and the form of expressing the variables were subsequently used in the multiple regression analyses (least-squares and "robust").

In multiple regression, the size of the dependent variable is assumed to equal the sum of the influences of several independent variables plus a random error. Consider n observations, each containing a value for the dependent variable (denoted by y_i, where $i = 1,\ldots,n$) and values for p independent variables (denoted by x_{ij}, where $j = 1,\ldots,p$ and $i = 1,\ldots,n$). In this study, the y_i are the yields and the x_{ij} include soil fertility measurements and dummy variables for the treatments. Further, consider the objective of choosing the coefficients β_j, where $j = 1,\ldots,p$, so that the prediction equation,

$$\hat{y}_i = \sum_{j=1}^{p} x_{ij}\beta_j, \quad (1)$$

gives predictions $\hat{y}_i$ close to the measured values of the dependent variable y_i. The β coefficients quantify the influences of the independent variables on the outcome.

There are various criteria for judging how close the predictions $\hat{y}_i$ are to the measured values y_i, one of which is the basis for ordinary multiple regression. The choice of criterion determines the β coefficients. Furthermore, the choice of criterion determines how well the residuals, $y_i - \hat{y}_i$, where $i = 1,\ldots,n$, can be used to choose among prediction equations with different independent variables. This choice, in turn, affects <u>all</u> the β coefficients (20).

The criteria used to compare the predictions and the measured values are functions of the residuals that have the following form,

$$\sum_{i=1}^{n} \rho(r_i/d), \quad (2)$$

where

$$r_i = y_i - \sum_{j=1}^{p} x_{ij}\beta_j, \quad (3)$$

d = scale factor,
$\rho(r_i/d)$ = function of r_i/d.

Two choices of ρ are to be discussed. They are shown in Figure 5 and are given by

$$\text{least-squares: } \rho(u) = u^2/2 \quad (4)$$

and

$$\text{Huber: } \rho(u) = \begin{cases} u^2/2, & \text{if } |u| \le 0.5 \\ 0.5|u| - 0.125, & \text{if } |u| > 0.5. \end{cases} \quad (5)$$

See Denby and Mallows (21) for a discussion of Huber.

The most notable difference among the choices of ρ is the relative importance placed on large and small residuals. Figure 5 shows that least-squares places more emphasis on large residuals than does Huber.

Some qualitative differences among the β coefficients and the residuals that minimize each of these criteria are now clear. Compared with least-squares, Huber gives predictions that are closer to the "easy-to-fit" points and further from "hard-to-fit" points. Thus, Huber gives both more small residuals and larger large residuals. Further, the β coefficients are influenced less by the "hard-to-fit" points. Huber gives residuals that are easier to use in choosing the prediction equation. Missing independent variables and independent variables that would fit better if reexpressed are diagnosed by plotting residuals vs. the variable in question. When the poorly fitting residuals are larger, they are easier to see.

These same properties of robust regression, as well as a computational algorithm, can be obtained by considering the equivalent for Huber of the normal equations for weighted least-squares. If for each observation the dependent variable has a different variance given by σ_i^2, where $i = 1,\ldots,n$, then weighted least-squares is more appropriate than ordinary least-squares. In this case, the criterion to be minimized is

$$\sum_{i=1}^{n} r_i^2/\sigma_i^2, \qquad (6)$$

and the β coefficients are computed by solving the equation,

$$\sum_{k=1}^{p} \left(\sum_{i-1}^{n} x_{ij}x_{ik}w_i\right) \beta_k = \sum_{i=1}^{n} x_{ij}y_iw_i, \qquad (7)$$

where $w_i = 1/\sigma_i^2$. For the two criteria discussed, the β coefficients satisfy equation 7, where $w_i = w(r_i/d)$ and

$$\text{least-squares:} \quad w(u) = 1 \qquad (8)$$

or

$$\text{Huber:} \quad w(u) = \begin{cases} 1, & \text{if } |u| \leq 0.5 \\ 0.5/\ u\ , & \text{if } |u| > 0.5. \end{cases} \qquad (9)$$

With Huber, the weights are data-dependent; that is, they depend on the size of the residual. In weighted least-squares, the higher the variance of an observation, the smaller is its weight and, consequently, the smaller is its influence on the β coefficients. With Huber, the larger the residual, the smaller is its weight and, consequently, the smaller is its influence. For Huber, equation 7 must be solved iteratively. An initial set of residuals is obtained, the corresponding weights are computed, and equation 7 is solved with these weights. This produces a new set of residuals on which to base the next iteration.

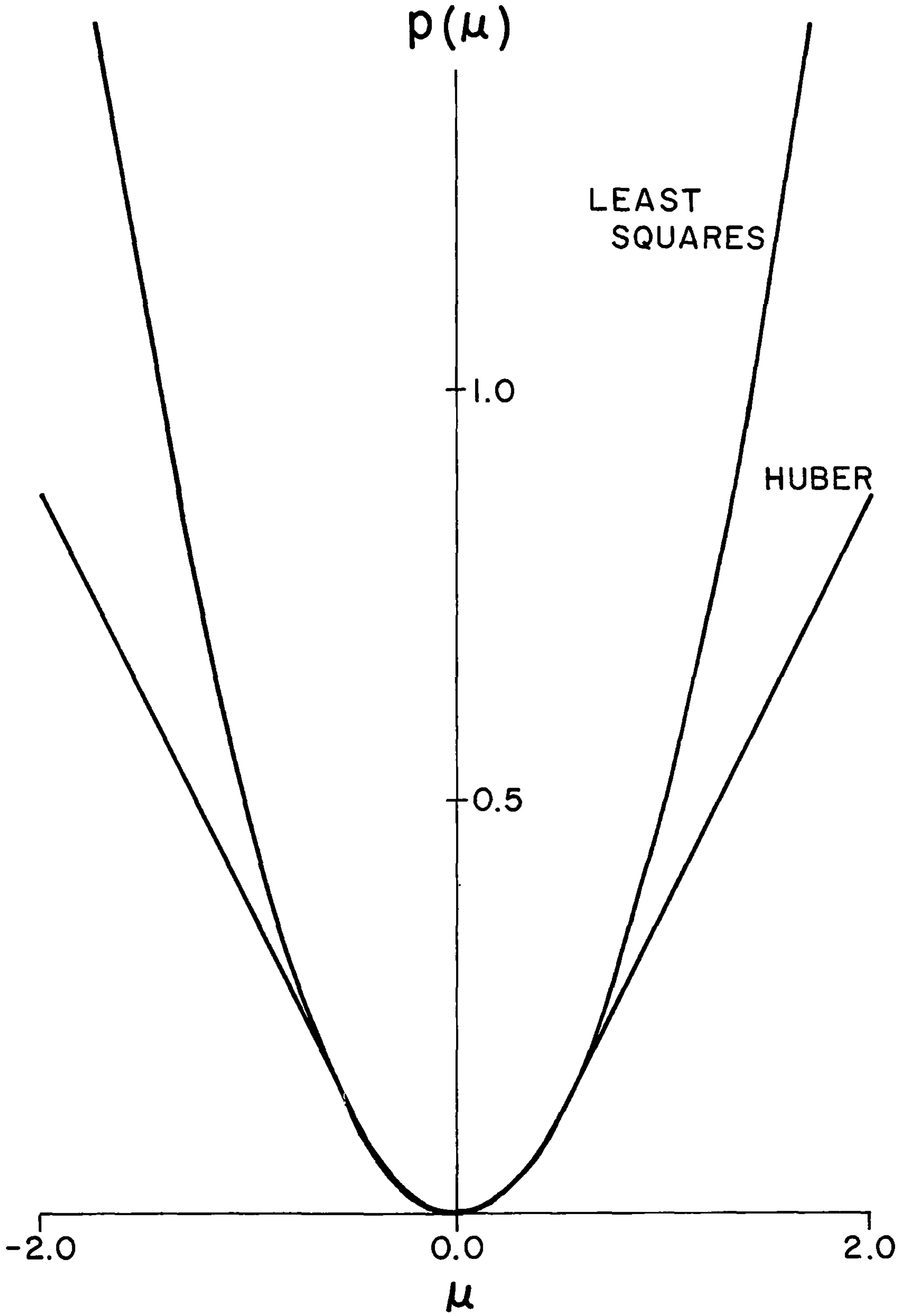

Figure 5. Comparison of effects of residuals on the size of the criteria: least-squares and Huber.

Consider finally the choice of scale factor. Denby and Mallows (21) discuss a procedure for choosing the scale factor for use with Huber. This procedure is followed in the analysis of the Sand Mountain plots. The scale factor that results is $d = 4.6$, which is equivalent to $h = 2.3$ in the paper by Denby and Mallows.

SECTION 4

RESULTS AND DISCUSSION

SURFACE AND SUBSURFACE CHARACTERISTICS OF EXPERIMENTAL SITES

The results of the measurements of depth to bedrock and relative elevation (appendix F) illustrate the greatest difficulty in selecting large experimental sites (i.e., obtaining an area that is large enough to accommodate the experimental design and that is uniform in surface and subsurface characteristics). An example of the three-dimensional output generated by computer graphics is presented in Figures 6a and 6b. These two figures show that, although the surface of the site (Figure 6a) appears uniform, the soil depth (Figure 6b) is quite variable. Because depth of the soil mass influences the water storage capacity, it is important to account for these differences in an analysis of within-site yield variability, particularly when rainfall is abnormal.

Response analysis of surface and subsurface characteristics was also useful in identifying drainage problems. Drainage ditches were installed at all sites during the winter and spring of 1977 to facilitate surface runoff and prevent wet spots. However, because internal drainage problems cannot be corrected, all plots (except those planted to pines) are scheduled to be planted to soybeans in 1977 in a further effort to characterize the yield potential of each plot and to determine the present degree of uniformity in growth and yield at each site.

EFFICIENCY OF AIR-EXCLUSION SYSTEM

Smoke and Fog Generator Tests

The results of these tests indicate that the air-exclusion system was least efficient when no plants were present. The smoke flowed around the air bags, and some smoke became trapped close to the ground between the bags. However, during the second test, when a canopy had formed, the system appeared more efficient at removing smoke from the plot. Although the smoke penetrated the canopy, it was quickly expelled from the top and sides of the plot. Smoke was expelled vigorously directly over the air bags and laterally along the edges of the plot below the plant canopy. Figure 7 shows penetration of the smoke into the plot. Figure 8 shows residual smoke within the plot immediately after the fog generator is turned off. Figure 9 shows the smoke being cleared from the plot directly over the air bag.

SO_2 Exposure Tests

The purpose of the SO_2 tests was to quantify the efficiency of the air-exclusion system. The first test showed that, when a concentration of 3670 $\mu g/m^3$ is present at the edge of the plot, the concentration inside the plot, at the center and just below the canopy, ranges

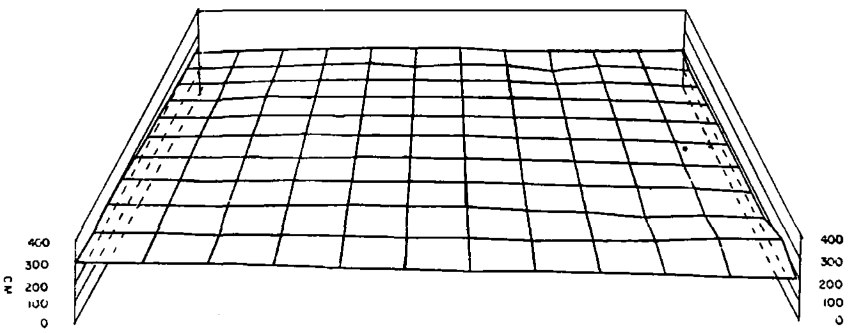

Figure 6a. Three-dimensional view of surface characteristics at site 10 (appendix A gives complete plot layout).

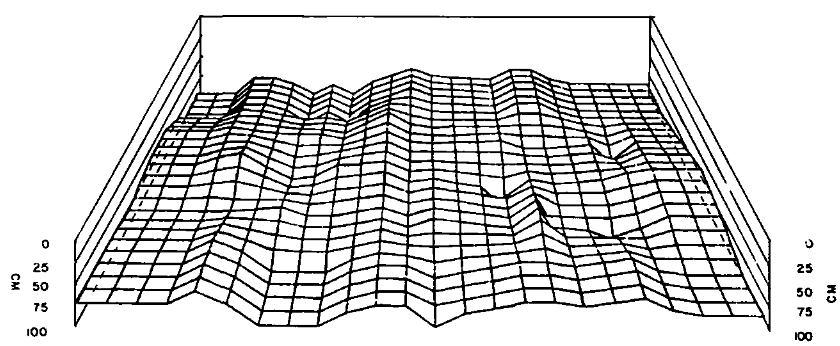

Figure 6b. Three-dimensional view of subsurface characteristics at site 10 (depth to bedrock).

Figure 7. Smoke from fog generator penetrating plant canopy.

Figure 8. Residual smoke within plant canopy immediately after fog generator is turned off.

Figure 9. Smoke from fog generator cleared from plant canopy after fog generator is turned off.

between 525 and 788 μg/m^3, an 83 percent reduction. However, it appears that some of the SO_2 becomes trapped below the canopy, and the concentration increases slightly. At 15 cm above ground, the concentration in the plot at several points within 3 m from the edge of the plot ranged from 655 to 850 μg/m^3. The concentration at 15 cm above ground decreased with increasing distance from the source of anhydrous SO_2. Concentrations measured along the edge of the plot inside the air barrier indicate that there is lateral transport of SO_2 below the canopy. At the farthest point from the source, in the southwest corner of the plot, the concentration at 30 cm above ground was 262 μg/m^3.

The SO_2 test that was performed with the fiberglass barrier (30 cm high) placed between the outer and inner buffer rows and at the north and south ends of the plot showed similar trends. The SO_2 concentration above the plot was 1100 μg/m^3. The concentration in the center of the plot, 5 m from the source and within the canopy, was 158 μg/m^3, a reduction of 85 percent. At 4 m from the source, the concentration within the canopy was 680 μg/m^3. At that same distance from the source, but at 7.5 cm above ground, the concentration was 324 μg/m^3, indicating that some SO_2 may become trapped below the canopy. There is indication that some lateral transport occurred in this test also because the concentration in the southeast corner of the plot (farthest point from the source) was 420 μg/m^3.

The second part of the test, with the air bags reduced to half their normal length, was complicated because of corresponding sampling points of the testing area that were closer to the source (i.e., the center of the plot in the first part of the test was 5 m from the source, whereas the center of the smaller plot in the second part of the test was 3 m from the source). Accordingly, the SO_2 concentration in the center of the plot climbed to 815 μg/m^3. Trapping and lateral transport was also indicated by a concentration of 5260 μg/m^3 below the canopy at the edge of the plot. When the air bags were inverted to increase air pressure below the canopy, the concentration within the canopy remained at 1280 μg/m^3.

The results of these tests should be interpreted with caution. Although an 83 to 85 percent reduction in SO_2 concentration was shown for the air-exclusion system, the magnitude of that reduction may result from the high initial concentration that was used in the tests. Also, the efficiency of the system undoubtedly varies with wind velocity. Because the wind velocity did not vary significantly during the tests, an evaluation of that variable is not possible.

Sulfation (Huey) Plate Tests

Sulfation plates were also used to quantify the efficiency of the air-exclusion system. Results of the analyses are presented in Figure 10. The average sulfation rate for the exposure period indicates that SO_2 in the exposed plots exceeded that of the air-exclusion plots by 32 percent at the 25-cm level, 63 percent at the 60-cm level, and 40 percent at the

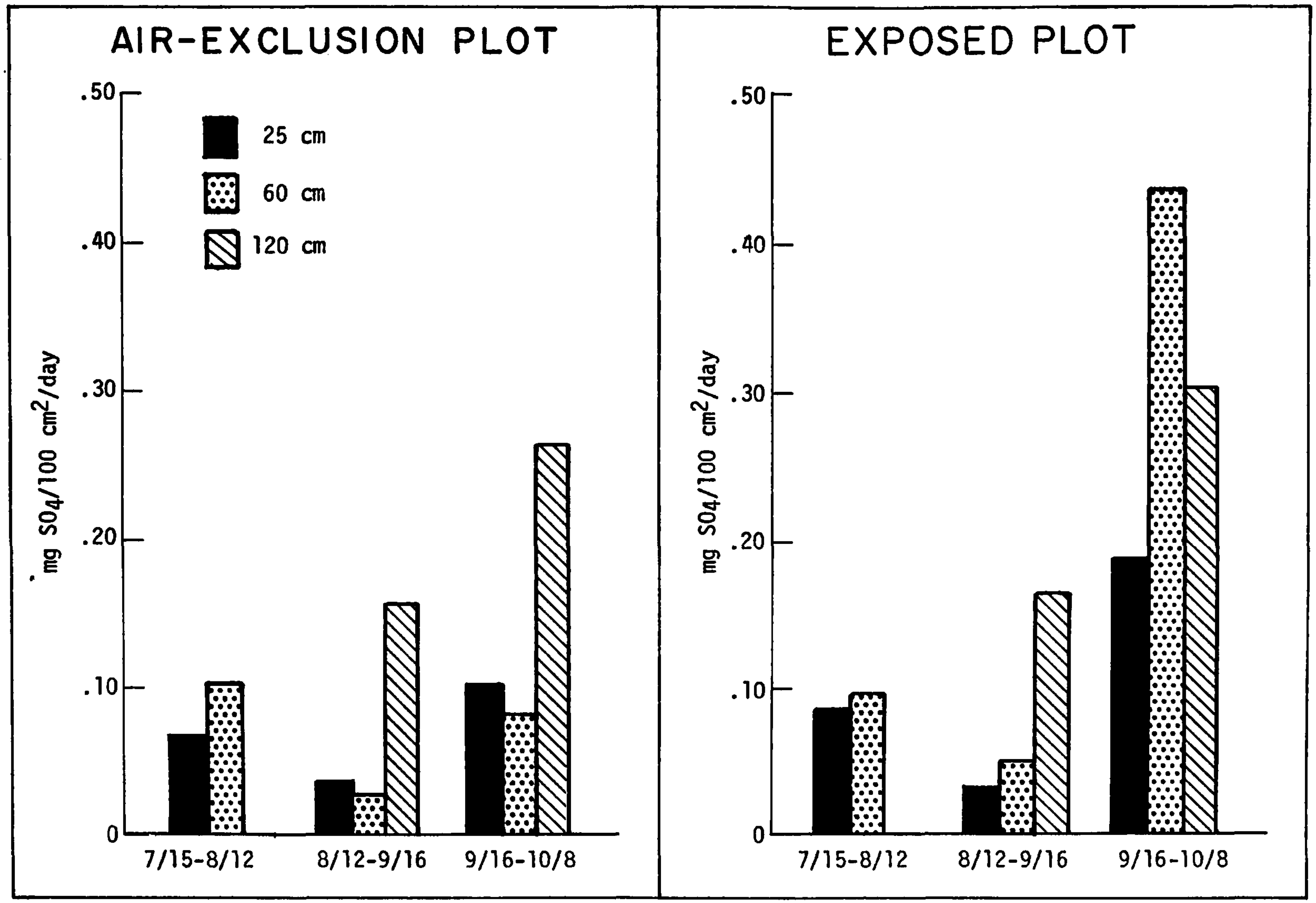

Figure 10. Monthly sulfation rates on three air-exclusion and two exposed plots at monitor 9.

120-cm level. Because the highest level (120 cm) was above the canopy throughout the exposure period, a large difference was not expected because exposure should have been about the same for both types of plots. Likewise, the difference at the shortest height (25 cm) was not expected to be large because the aerodynamic effect of the canopy should exclude some of the pollutant, and the amount of SO_2 that becomes trapped close to the ground under the canopy would be similar in both types of plots as indicated by the aforementioned SO_2 exposure tests. The difference between the two types of plots at the 60-cm level is of interest because the smoke tests have shown that the air-exclusion system is effective in clearing smoke from the region. The percentage difference may be conservative because the plates were above the plant canopy for a brief period of time.

Foliar Sulfur Analysis

The sulfur content of foliage of soybeans (Table 1) grown on the exposed plots at sites 6 and 9 was significantly higher than that of soybeans grown on the air-exclusion plots at the same sites. When the variance for treatments at sites 6, 9, and 10 was pooled, the foliar sulfur content was significantly higher for exposed plots as compared with that for air-exclusion plots.

TABLE 1. SULFUR CONTENT OF SOYBEAN FOLIAGE ON AIR-EXCLUSION AND EXPOSED PLOTS AT MONITORS 6, 9, 10, AND 22

Monitor No.	Total sulfur (%)[a] Air-exclusion plots	Exposed plots
6	0.170	0.227[b]
9	0.150	0.177[b]
10	0.157	0.157
22	0.127	0.147

a. Each value is an average of three plots.
b. Difference between treatment and control is significant at the 5 percent level.

These results would seem to indicate a much lower efficiency rating for the air-exclusion system than indicated by the sulfation plates or the SO_2 exposure tests. However, because the foliar samples were collected from the inner buffer rows of the plots, the measurements may not be representative of sulfur levels present in the interior of the plots. Also, the contribution to the foliage of sulfur from the soil environment may be so great as to mask the contribution from the atmosphere.

ENVIRONMENTAL MONITORING

Sulfur Dioxide

During the 1976 growing season there were 14 occasions on which SO_2 concentrations equaled or exceeded 1306 μg/m^3 (0.5 ppm) 1-h average during daylight hours at sites 6, 9, and 10 near the steam plant (Table 2); there were six occasions on which concentrations equaled or exceeded 1306 μg/m^3 for 3 h. During the pod-filling stage of growth, when soybeans should be most sensitive to yield reduction from foliar injury, there were four occasions on which concentrations equaled or exceeded 1306 μg/m^3 3-h average.

The highest total exposure above 262 μg/m^3 during daylight hours was registered at monitor 10 (Table 3), whereas the highest 1-h average concentration was registered at site 6 (Table 4). The only occurrence of foliar injury that was great enough to be distinguished from that caused by other factors in the environment was observed for the control plots at site 6 after an exposure on August 13 during which the maximum 1-h average SO_2 concentration was 2351 μg/m^3 (0.90 ppm). No concentrations of 262 μg/m^3 or more were registered at site 22.

TABLE 2. NUMBER OF OCCURRENCES OF SULFUR DIOXIDE EXPOSURES EQUAL TO OR GREATER THAN 1300 μg/m^3 1-H OR 3-H AVERAGE

	1-h average ($\geq$ 1300 μg/m^3)		3-h average ($\geq$ 1300 μg/m^3)	
Site	Growing season (occurrences)	After Aug. 12 (occurrences)	Growing season (occurrences)	After Aug. 12 (occurrences)
6	4	4	2	2
9	1	1	0	0
10	3	1	1	1
19	6	3	3	1

TABLE 3. TOTAL EXPOSURE TO SULFUR DIOXIDE CONCENTRATION EQUAL TO OR GREATER THAN 262 μg/m³ DURING DAYLIGHT HOURS[a] FOR 1976 GROWING SEASON

Monitor	Exposure (h)	Total SO_2[b] (ppm)	Total SO_2[b] (μg/m³)	Dose (μg m^{-3} h^{-1})
6	65	16.68	43,703	2,854,630
9	67	12.12	31,754	2,127,518
10	73	16.21	42,470	3,100,310
19[c]	-	-	-	-

a. 6:00 a.m.-7:00 p.m. CDT.
b. Cumulative total above 262 μg/m³.
c. Not calculated because plot was abandoned.

TABLE 4. MAXIMUM 1-H AND 3-H AVERAGE SULFUR DIOXIDE CONCENTRATIONS RECORDED AT STUDY SITES 6, 9, 10, AND 19 DURING 1976 SOYBEAN GROWING SEASON

Monitor	Date	Maximum 1-h average (μg/m³)	Maximum 3-h average (μg/m³)
6	8/13	2,351	1,463
9	8/21	1,515	1,097
10	8/14	2,194	1,515
19	7/24	10,318	4,519

Ozone

Ozone levels were measured at site 9 from July 1 until September 21, 1976. Some data were lost because of a malfunction in the recorder. Data are reported in central daylight saving time (CDT). In reading the charts and tabulating the data, the average concentration was recorded for each hour beginning at 12 midnight. The results show that the national primary-secondary air quality standard for O_3 of 160 μg/m³ was exceeded on 27 days. The monthly average of hourly O_3 concentration and the monthly average of these daily maximum concentrations are presented in Table 5.

TABLE 5. MONTHLY AVERAGE OF HOURLY OZONE CONCENTRATION AND MONTHLY AVERAGE OF DAILY MAXIMUM OZONE CONCENTRATION

Period	No. of days monitored	Monthly average concentrations: Hourly ozone ($\mu g/m^3$)	Daily maximum ozone ($\mu g/m^3$)
7/1 to 7/31	29.5	115.6	150.9
8/1 to 8/31	29.1	88.2	135.2
9/1 to 9/21	20.8	78.2	111.7

The highest concentration, which was recorded on five separate days, was 235 $\mu g/m^3$. These results indicate that the potential for O_3 injury to soybeans exists in the Widows Creek area. A concentration of 196 to 235 $\mu g/m^3$ has been shown to be injurious to a number of plant species.

FOLIAR INJURY, GROWTH, AND YIELD OF SOYBEANS

Foliar Injury

The amount of foliar injury that occurred on the study plots during the 1976 growing season (appendix G) was small and variable, averaging about 2 percent or less for all sites during the pod-filling stage of growth (Table 6). The only chlorosis that could be confidently attributed to exposure to SO_2 occurred at site 6 on August 13 during an exposure in which a maximum 1-h average SO_2 concentration of 2351 $\mu g/m^3$ was recorded. The percentage of leaf area exhibiting chlorosis for the exposure averaged 1.0 and 6.4 percent for the air-exclusion and exposed plots, respectively. The maximum percentage chlorosis for samples within treatments was 8.5 and 30.0 for the air-exclusion and exposed plots, respectively. The levels of chlorosis for the two treatments were significantly different at the 0.05 level of probability. Differences between treatments for the other sites or for other exposures were not significant. The data indicate a trend toward protection of the plots by the air-exclusion systems.

TABLE 6. FOLIAR CHLOROSIS OF SOYBEAN ON STUDY SITES DURING THE POD-FILLING STAGE OF GROWTH

Site	Total leaf area affected (%)	
	Maximum average weekly observation[a]	Average of weekly observations[b]
6		
Air-exclusion	0.9	1.0
Exposed	6.4	2.1
9		
Air-exclusion	0.2	0.3
Exposed	2.1	0.9
10		
Air-exclusion	0.5	0.2
Exposed	0.3	0.2
22		
Air-exclusion	0.3	0.5
Exposed	0.1	0.2

a. Based on maximum for exposed plot.
b. Four weeks of observations.

Height Growth

There were no significant differences in height growth between treatments at sites 6, 10, and 22 (Table 7). The difference at site 19 was attributed to the extremely shallow soils of the exposed plots. This site was abandoned, and a new study site was established at monitor 25 at the end of the growing season.

TABLE 7. AVERAGE HEIGHT GROWTH OF SOYBEANS BY TREATMENT FOR ALL SITES

Site No.	Height growth (cm)[a]		
	Air-exclusion	Exposed with plastic	Exposed without plastic
6	104	108	107[b]
9	108	110	113[b]
10	95	98	95[b]
19	110	53	
22	96	98[b]	

a. Height measurements taken the week of August 25.
b. Underscored indicates treatments at the same site not significantly different from each other at the 5 percent level.

Yields

Analysis of variance indicated no significant differences in yield (Table 8; appendix H) between air-exclusion plots and their comparable exposed plots (with simulated plastic tubes) at any of the sites except 6 and 19. However, except for the exposed plots without plastic treatment at site 9, higher yields were produced on all sites with the air-exclusion treatment. The exceptions at site 9 may have resulted from air-exclusion plots 1 and 2 having been cropped in soybeans in previous years; plots 10, 16, and 17 were all located on new ground. Jones et al. (10,11) have observed that continuous cropping in soybeans results in reduced yields. The differences at site 19 were caused by the shallow soil and were reflected in the much reduced height of the plants, as discussed previously. Although significant differences in yields occurred between exposed plots with plastic and those without plastic at sites 9 and 10, there was no consistent relationship in differences. The differences are attributable to edaphic factors: the pH of exposed plots without plastic was very low on plots at site 10, which can result in reduced yields, and the plots of the same treatment at site 9 were all on new ground, which can result in increased yields.

The results at site 22 indicate that the air-exclusion system does not adversely affect the growth and yield of soybean plants. However, the yields at the remote site were considerably lower than those for the sites in the area exposed to emissions from the power plant. The lower yields probably reflect the generally lower soil fertility at the site and less precipitation during the pod-filling stage.

TABLE 8. AVERAGE SOYBEAN YIELD BY TREATMENT FOR ALL SITES

Site No.	Yield (kg/ha)[a] Air-exclusion	Exposed with plastic	Exposed without plastic
6	3,294	2,881	2,903[b]
9	3,006	2,910[b]	3,320
10	3,615	3,538[b]	2,743
19	3,120	1,149	
22	2,707	2,554	

a. Oven-dry weight.
b. Underscored indicates treatments at the same site are not significantly different from each other at the 5 percent level.

Bean weights were compared by ANOVA for the treatments at site 6 to determine whether the significantly lower yields on the exposed plots were reflected on smaller beans; the test showed no difference in averages (Table 9).

TABLE 9. AVERAGE WEIGHT OF 100 SOYBEAN SEED BY TREATMENT AT MONITOR 6

Treatment	Sample weight (g)[a]
Air-exclusion plots	14.31
Exposed (plots with plastic)	14.32
Exposed (plots without plastic)	13.73

a. Each mean is an average of 10 replicate samples of 100 beans each from three sampling rows from three plots.

Because the plants at site 6 were exposed to higher concentrations of SO_2 and exhibited more chlorosis, which could be attributed to SO_2 exposure, it would appear that the reduced yields of the control plots were caused by SO_2; however, the data are not conclusive. Part of the difference in yields within site 6 may have been caused by lower P levels in the soils of the exposed plots. The difference between the exposed plots at site 6 and the plots at the other sites also suggests a yield reduction, but this may be a result of site differences not reflected in the available measurements. Furthermore, there was little difference between the average percentage chlorosis over the entire pod-filling stage for the exposed plants compared with that for the air-exclusion plots at site 6 or other sites.

The plots on Sand Mountain differ in ways other than their exposure to the plume from the Widows Creek Steam Plant. These differences--the most important of which are in the P, K, Mg, and organic matter contents of the soil--are suspected to be additional causes of differences in yield. To separate these effects on the yields, a model for the yields has been fit to the data.

The model contains seven predictor variables, two variables that account for conditions unique to particular sets of plots and five variables that account for the soil fertility. Foliar sulfur measurements, the SO_2 monitoring results, and the yield measurements themselves suggest that the exposed plots at site 6 were affected by the power plant; thus, a variable EXP is included to give the difference in yield resulting from this exposure. The possibility exists that there are conditions affecting the yield at site 6 that are not reflected in the measured factors. A variable SITE6 is included to give the difference resulting from these conditions. The inclusion of this variable ensures that the coefficient of EXP reflects only the difference between the three protected and six unprotected plots at site 6 and not the difference between site 6 and the other two sites. The soil-content variables included are the logarithms of the P, K, and Mg and the percentage of organic matter. Both linear and quadratic terms in the logarithm of the P are included.

The estimated effect of the exposure is -222 kg/ha with a standard error of 147 kg/ha. The estimated effect of the unmeasured conditions peculiar to site 6 is -207 kg/ha with a standard error of 150 kg/ha. These standard errors are not small enough for these effects to be clearly distinguished from the random variability in the yields. If no variable were included to account for the peculiarities of site 6, then the effect of the exposure would be significant at the 0.01 level. In other words, comparison of the exposed plots at site 6 with all other plots on Sand Mountain shows a reduction in yield not accounted for by the soil fertility variables included in the model.

The model is given by

$$\begin{aligned}\text{YIELD (kg/ha)} = 4448 &- 222\ \text{EXP} - 207\ \text{SITE6} - 1410(\text{LP}-2.14)^2 \\ &- 1602\ \text{LK} + 972\ \text{LMG} + 391\ \text{OM},\end{aligned} \tag{10}$$

where

LP = base 10 logarithm of the P, kg/ha,
LK = base 10 logarithm of the K, kg/ha,
LMG = base 10 logarithm of the Mg, kg/ha,
OM = percentage organic matter.

The variable EXP has the value 1 for the exposed plots at site 6 and the value 0 elsewhere. The variable SITE6 has the value 1 for the plots at site 6 and the value 0 elsewhere. According to the model, the best P content is 235 kg/ha. The K content is so high that for these plots an increase in K has a negative effect on yield. Increases in either Mg or organic matter have a positive effect on yield. The term LMG - LK represents an interaction term that can also be expressed as base 10 logarithm of the Mg/K ratio; that is, at low levels of Mg, increased K levels have a negative effect on yield. Stepwise regression analysis of the data (appendix I) gave a model that was similar to the least-squares model in explaining variations in yield among the plots; that is,

$$\text{YIELD (kg/ha)} = 2882 - 279\ \text{EXP} - 337\ \text{SITE6} - 972(\text{LP}-2.14)^2 + 879\ \text{L Mg/K} + 448\ \text{OM}\ (r^2 = 0.74). \quad (11)$$

However, the quadratic term in P was dropped from the regression model because it was not significant at the 10 percent level. The final model was

$$\text{YIELD (kg/ha)} = 2878 - 300\ \text{EXP} - 316\ \text{SITE6} + 936\ \text{L Mg/K} + 434\ \text{OM}\ (r^2 = 0.72). \quad (12)$$

The interaction term (L Mg/K) was the most significant variable explaining variation in yields among all the experimental plots. The Mg/K interaction has been reported by other investigators (22). The analyses also indicated that, for soils with high OM, larger amounts of Ca were required to raise the pH than for soils with lower levels of OM.

The standard errors for equation 10 are 295 for the linear term in LP, 893 for the quadratic term in LP, 562 for LK, 162 for LMG, and 162 for OM. The standard error for the coefficient of the quadratic term in P indicates that it is not significantly different from zero. Excluding this variable would have two consequences: (1) two large negative residuals appear that seem attributable to excess P; (2) for site 6, the effect of increasing P on yield becomes less, and, to compensate, the effect of the exposure becomes large enough to be significant at the 0.05 level.

The goodness of fit of the model is determined by examining the residuals, the differences between the actual yields, and the yields predicted by the model. First, the residuals are plotted vs. variables not in the model to determine whether these variables should be included. Second, the residuals are plotted vs. the variables in the model to determine whether a transformation would give a better fit. Third, the residuals are plotted vs. the fitted yields to determine whether the fit is good at the ends of the range of yields. Because the model is a least-squares fit, the residuals, considered as a vector, are perpendicular to the variables in the model. For this reason, more sensitivity is obtained by plotting vs. variables that have been adjusted to remove their dependence on the variables in the model. For variables not in the model, the usual correlation formula applied to the points plotted gives partial correlations.

Figures 11 through 13 show the residuals plotted vs. the soil pH, the base 10 logarithm of the Ca content of the soil, and the index of injury due to disease and insects (each variable adjusted to remove its dependence on the variables in the model). Figure 11 suggests that a weak positive dependence on pH holds except for the four points furthest right, which have pH values of 6.7, 6.7, 6.6, and 6.5. The negative residuals for these four plots may be explained by something other than excessive pH. Thus, pH was not included in the model. Figure 12 suggests that a weak positive dependence on Ca holds except for a few points. Figure 13 shows no dependence on the insect-disease index.

Figures 14 through 17 show the residuals plotted vs. LP, LK, LMG, and OM, each adjusted for the variables in the model except itself. Figure 14 shows no dependence. Figure 15 shows that the most negative residual has very low K, perhaps so low that the negative dependence on K that is part of the model does not hold. Results of a decrease in the influence of this point on the model are discussed below. Neither Figure 16 nor Figure 17 shows any dependence.

Often the poorest fit occurs for the largest or smallest predicted values. To allow this to be checked, Figure 18 shows the residuals plotted vs. the fit. It shows no evidence of poor fit at the ends of the range.

Some data points may not fit the model very well, not because of the random variability in the yields, but because of effects not included in the model. Least-squares fits are unduly influenced by such points. The procedure suggested by Denby and Mallows (21) gives a sequence of robust fits that are influenced less and less by such points.

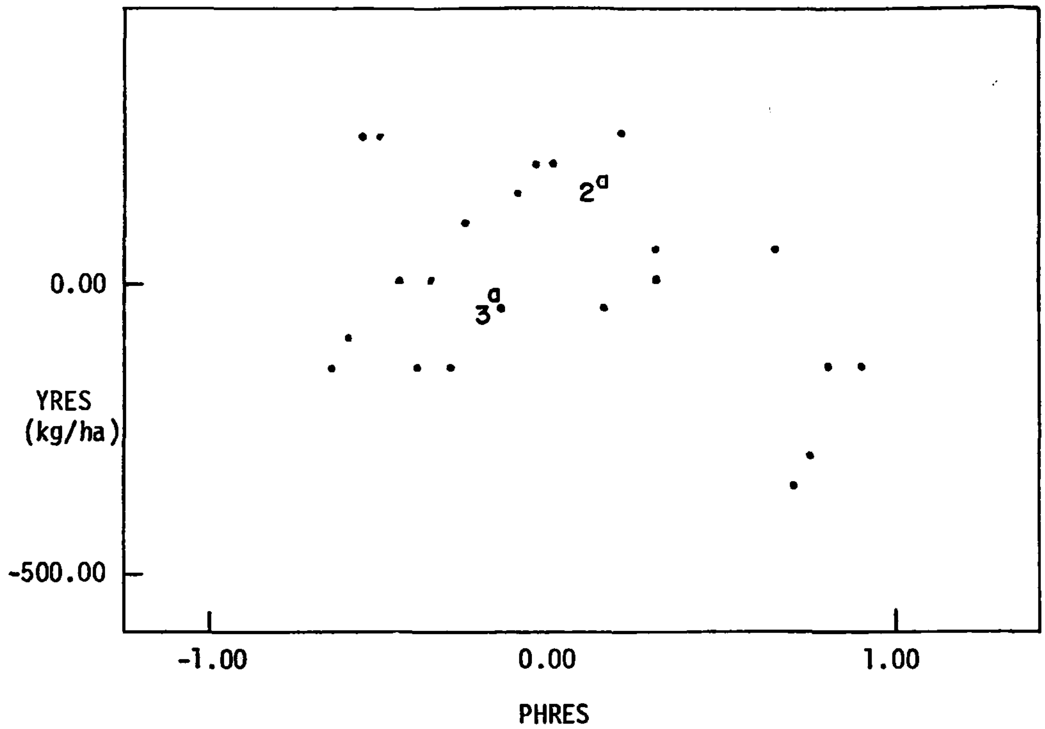

Figure 11. Yield residuals (YRES) vs. soil pH residual (PHRES) adjusted for variables in model.

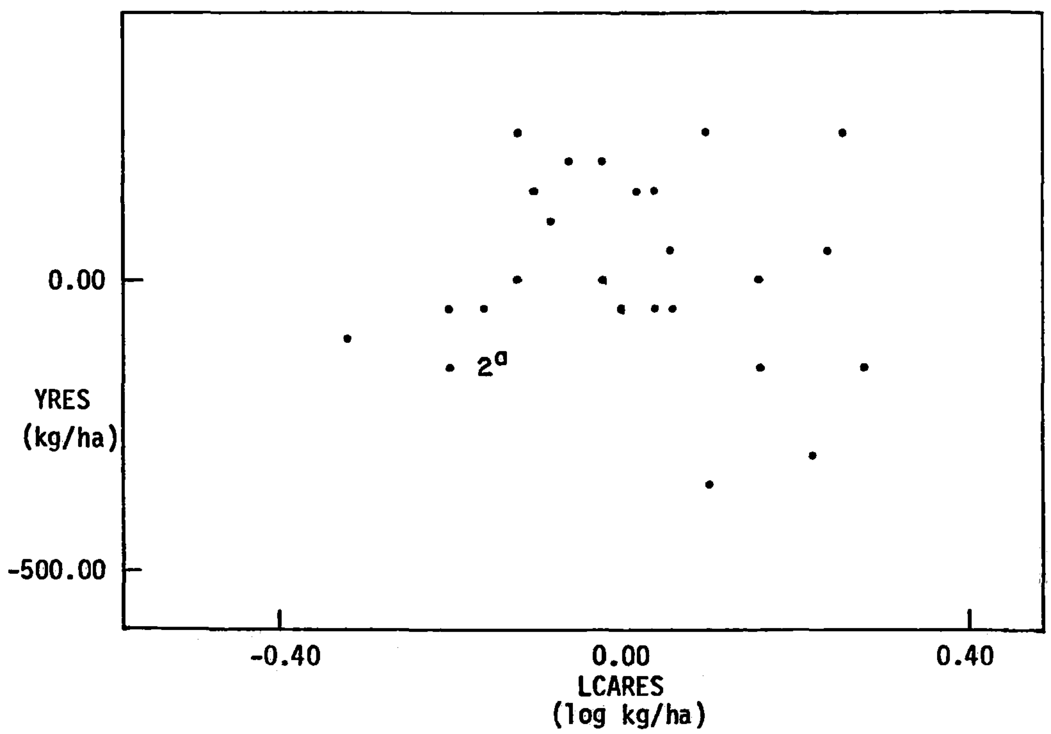

Figure 12. Yield residuals (YRES) vs. log calcium residual (LCARES) adjusted for variables in model.

a. number of multiple observations at same value.

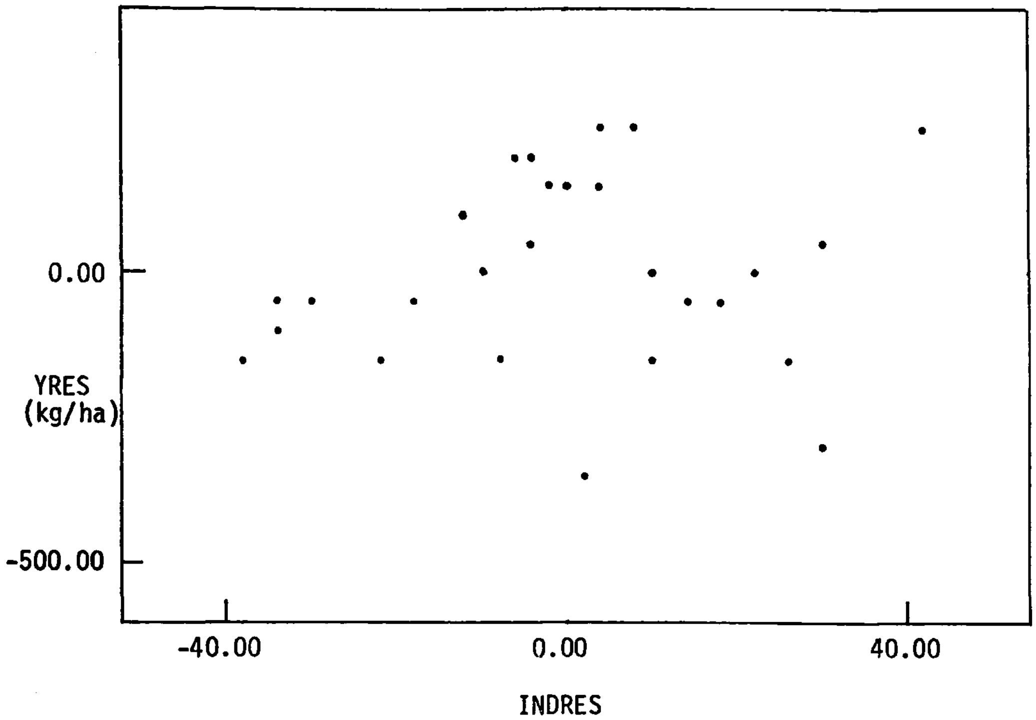

Figure 13. Yield residuals (YRES) vs. insect-disease index residual (INDRES) adjusted for variables in model.

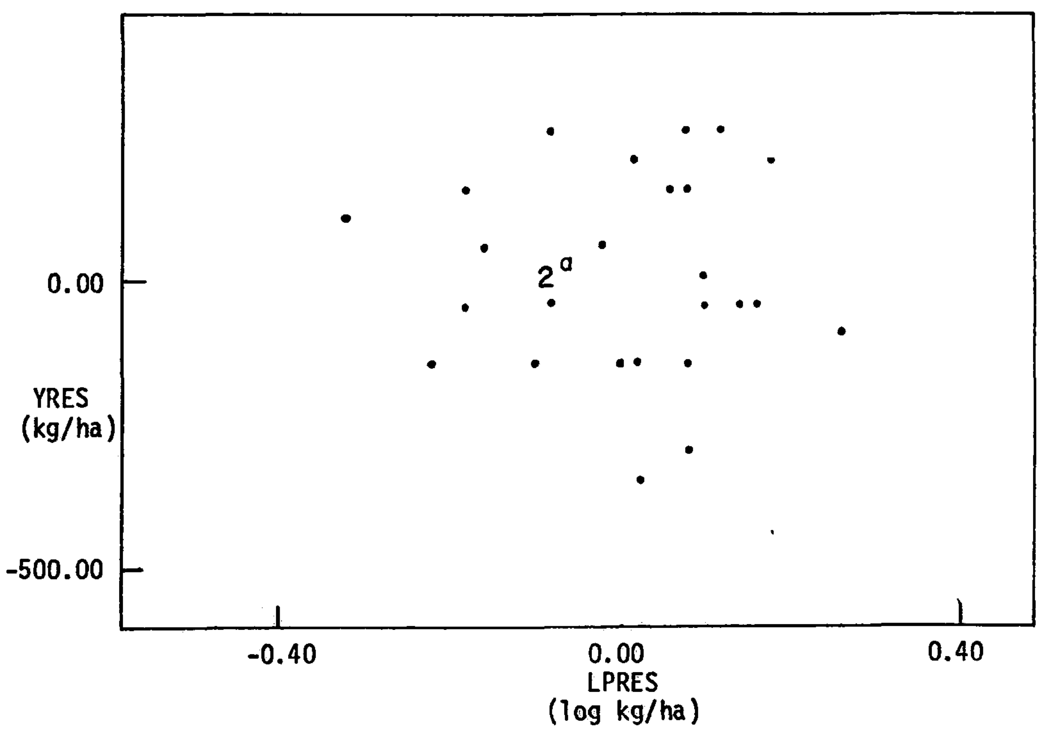

Figure 14. Yield residuals (YRES) vs. log phosphorus residual (LPRES) adjusted for other variables in model.

a. number of multiple observations at same value.

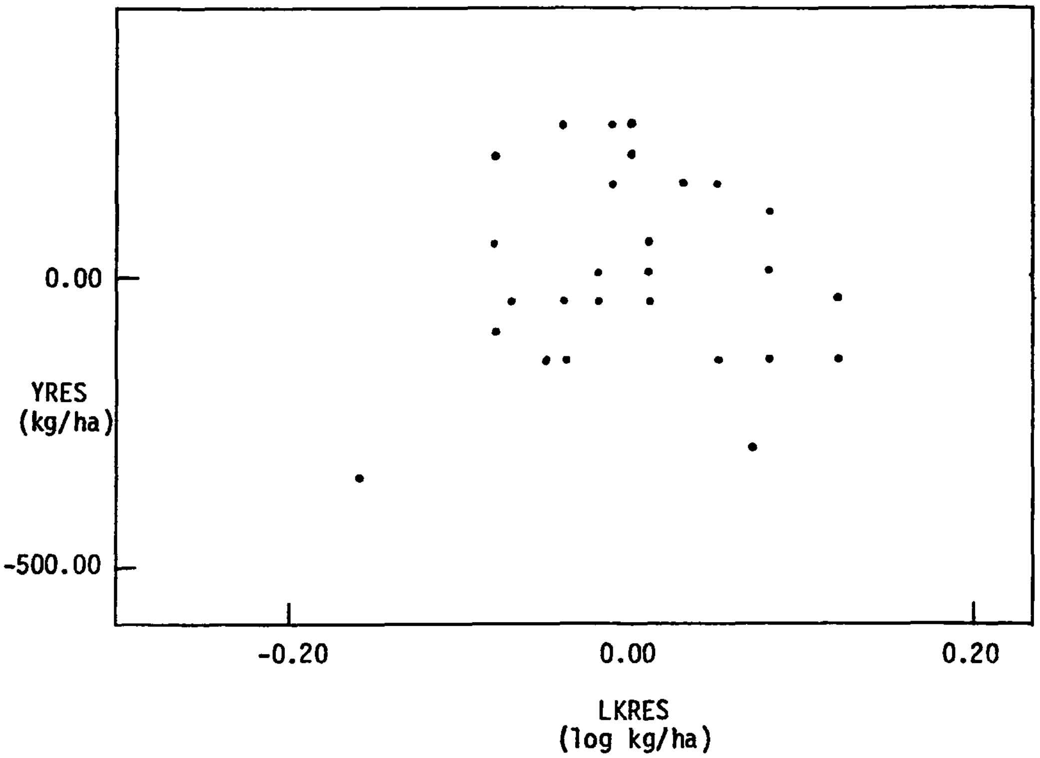

Figure 15. Yield residuals (YRES) vs. log potassium residual (LKRES) adjusted for other variables in model.

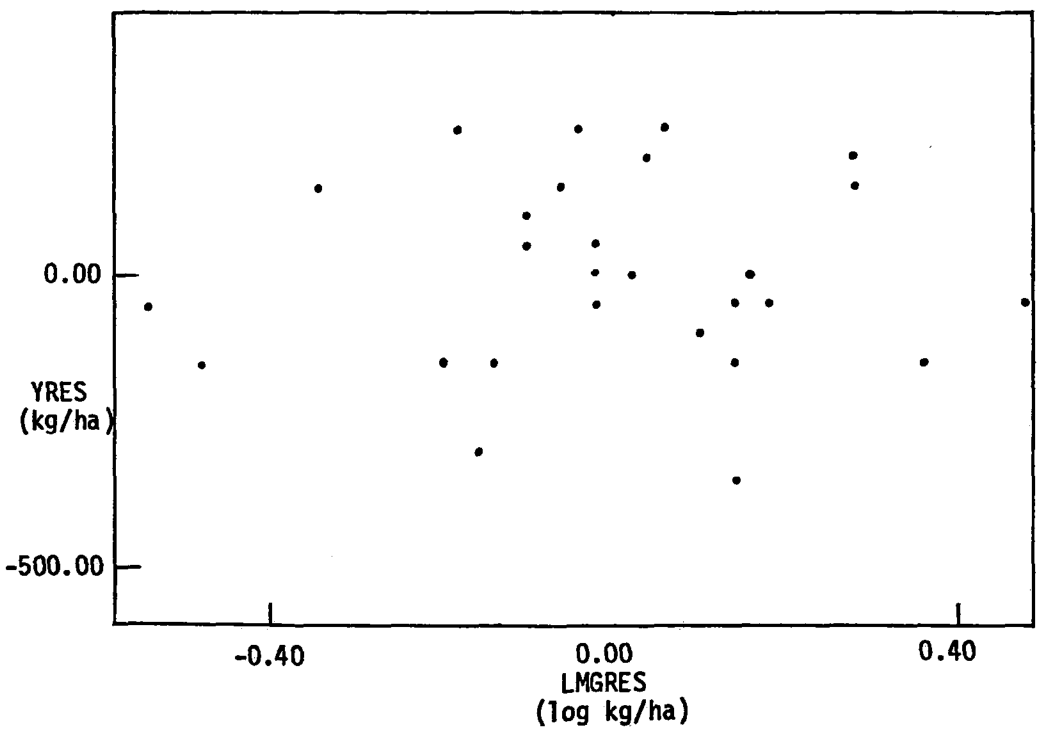

Figure 16. Yield residuals (YRES) vs. log magnesium residual (LMGRES) adjusted for other variables in model.

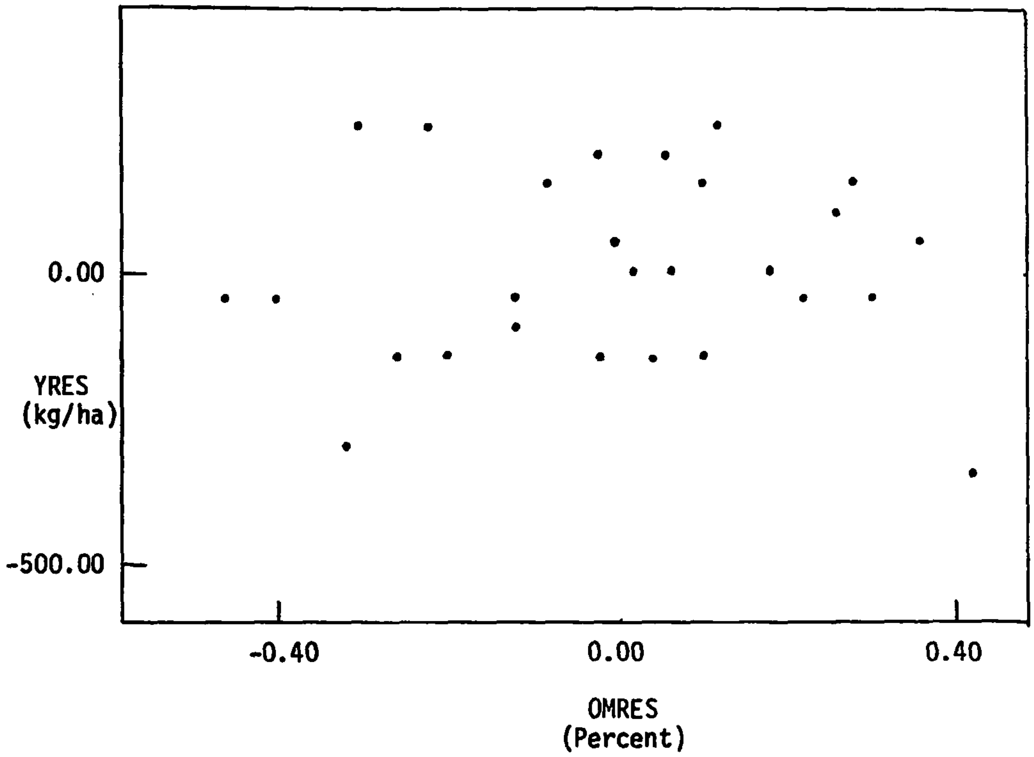

Figure 17. Yield residuals (YRES) vs. percent organic matter residual (OMRES) adjusted for other variables in model.

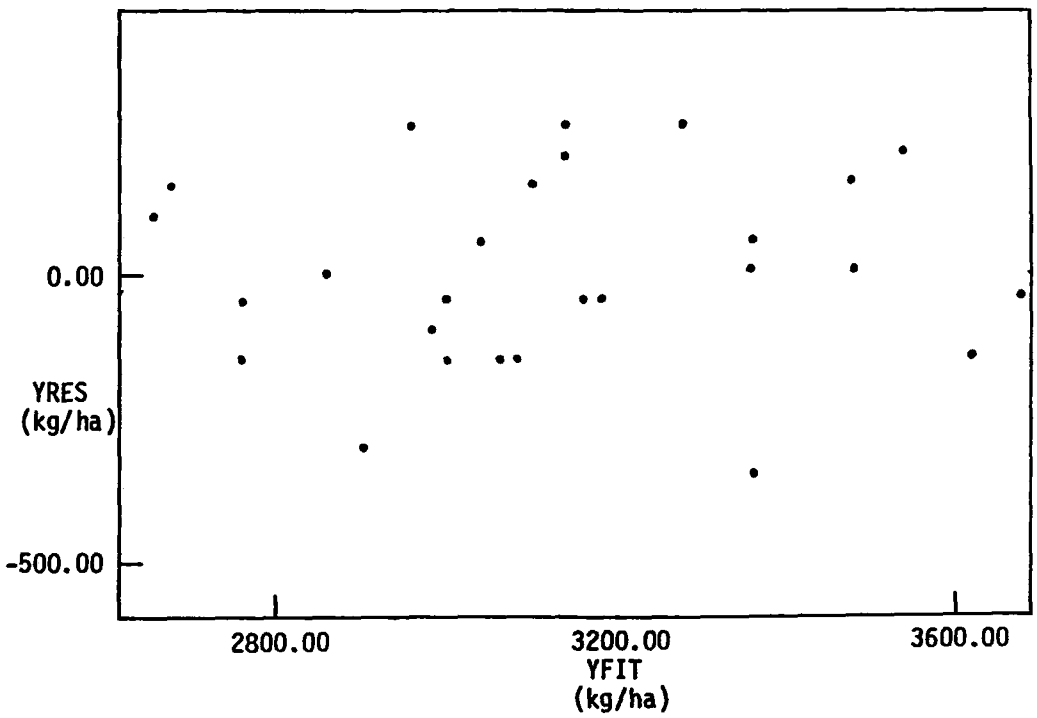

Figure 18. Yield residuals (YRES) vs. fitted yields (YFIT).

The model given by robust fitting is

$$YIELD = 4928 - 256\ EXP - 236\ SITE6 - 1332\ (LP-2.14)^2 - 1602\ LK + 972\ LMG + 391\ OM. \qquad (13)$$

This model does not differ from the least-squares model enough to change the conclusions.

Often the most valuable output from a robust fit is a set of residuals containing unusually large values for the unusual data points. In this case, the residual for the plot with lowest K changes from -352.1 to -465.8. The two residuals that decreased the most were those for the two plots with lowest K, and the two residuals that increased the most were those for the two plots with highest K. This shows the effect of decreasing the influence of the observation with lowest K. Additionally, the robust residuals do suggest that some other plots are unusual, perhaps because of soil variations within sites. The least-squares and robust residuals are shown in Table 10. This information is useful in designing future experiments for these plots to minimize the bias that may be introduced by differences in site factors and location.

TABLE 10. LEAST-SQUARES AND ROBUST RESIDUALS

Site	Plot	Least-squares	Robust
6	1	34.0	2.3
6	2	5.2	4.7
6	3	28.7	-7.0
6	13	150.4	191.9
6	15	-42.9	3.5
6	16	-140.8	-115.9
6	9	91.7	65.0
6	20	74.1	-85.4
6	22	15.8	-1.8
9	1	56.0	-8.2
9	2	-352.1	-465.8
9	7	-88.2	-85.4
9	15	148.0	134.6
9	13	-311.2	-239.3
9	14	-163.9	-123.5
9	10	245.2	223.5
9	16	209.9	186.7
9	17	266.4	296.7
10	1	-69.1	-72.6
10	2	199.9	220.6
10	3	230.80	246.9
10	4	-162.9	-156.8
10	5	126.1	-103.6
10	6	70.0	-39.8
10	17	169.9	-176.1
10	18	18.3	50.3
10	19	138.9	114.1

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APPENDIX A

PLOT ARRANGEMENT AT EACH SITE AND DIRECTION FROM STEAM PLANT

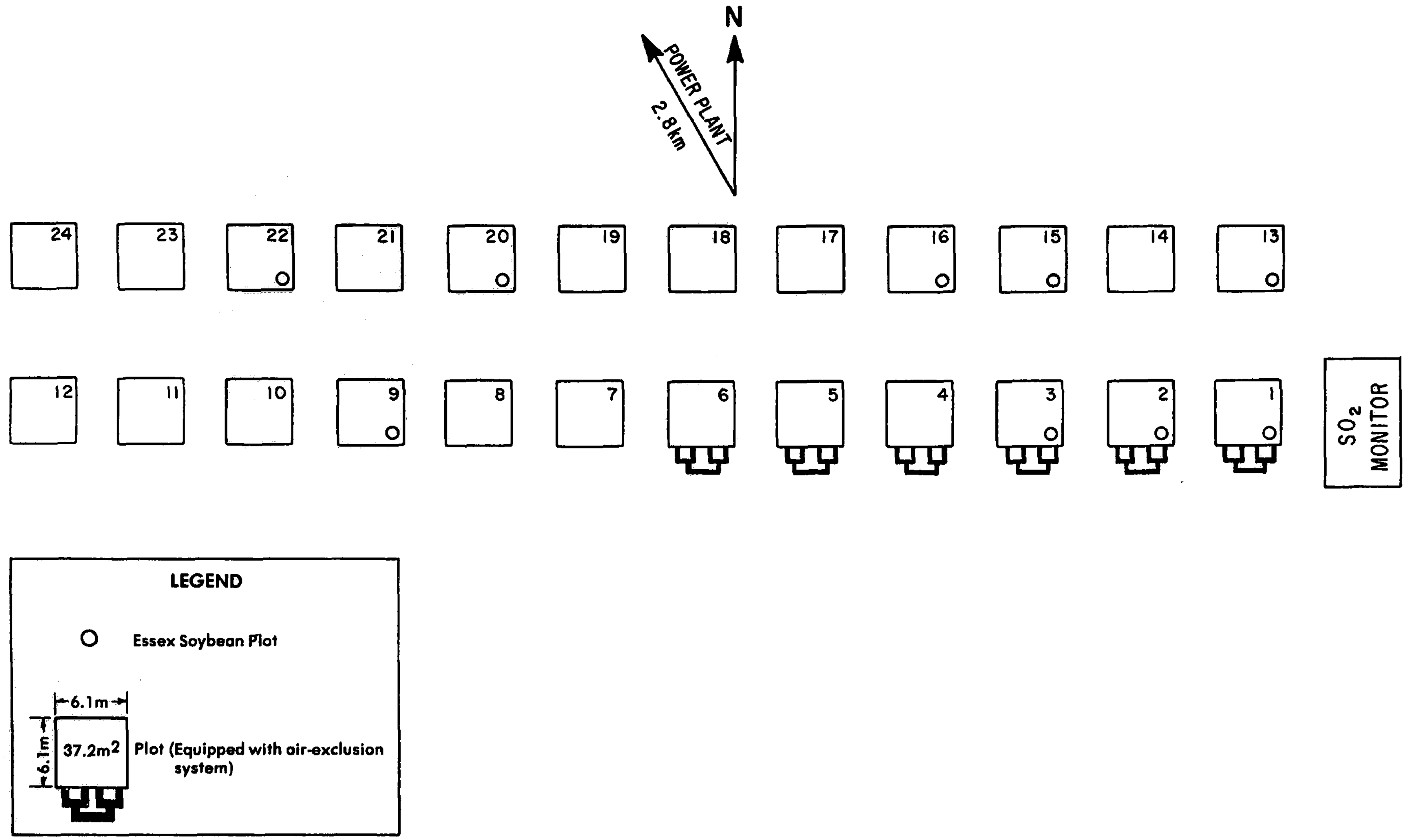

Figure A1. Plot arrangement, monitor 6.

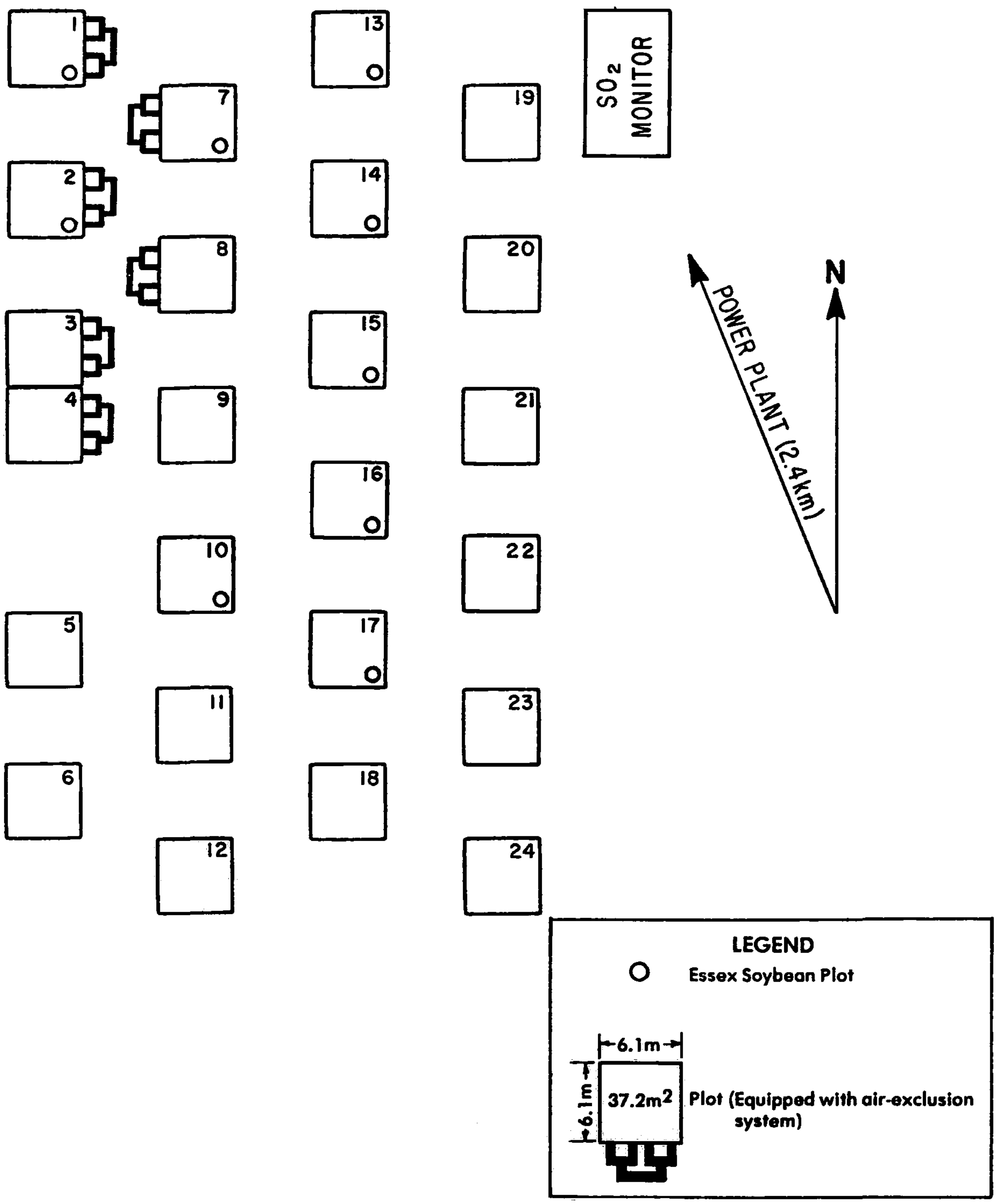

Figure A2. Plot arrangement, monitor 9.

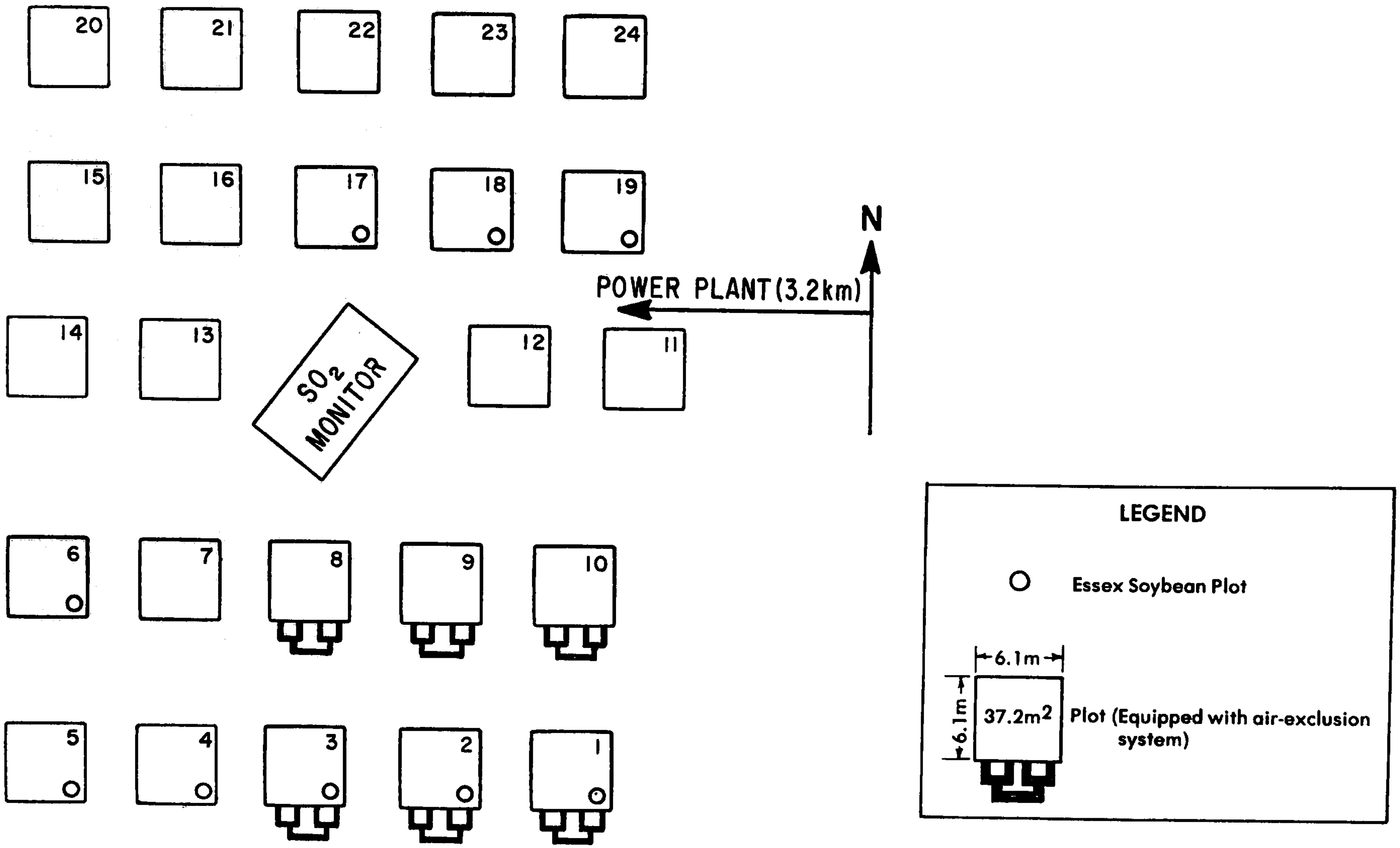

Figure A3. Plot arrangement, monitor 10.

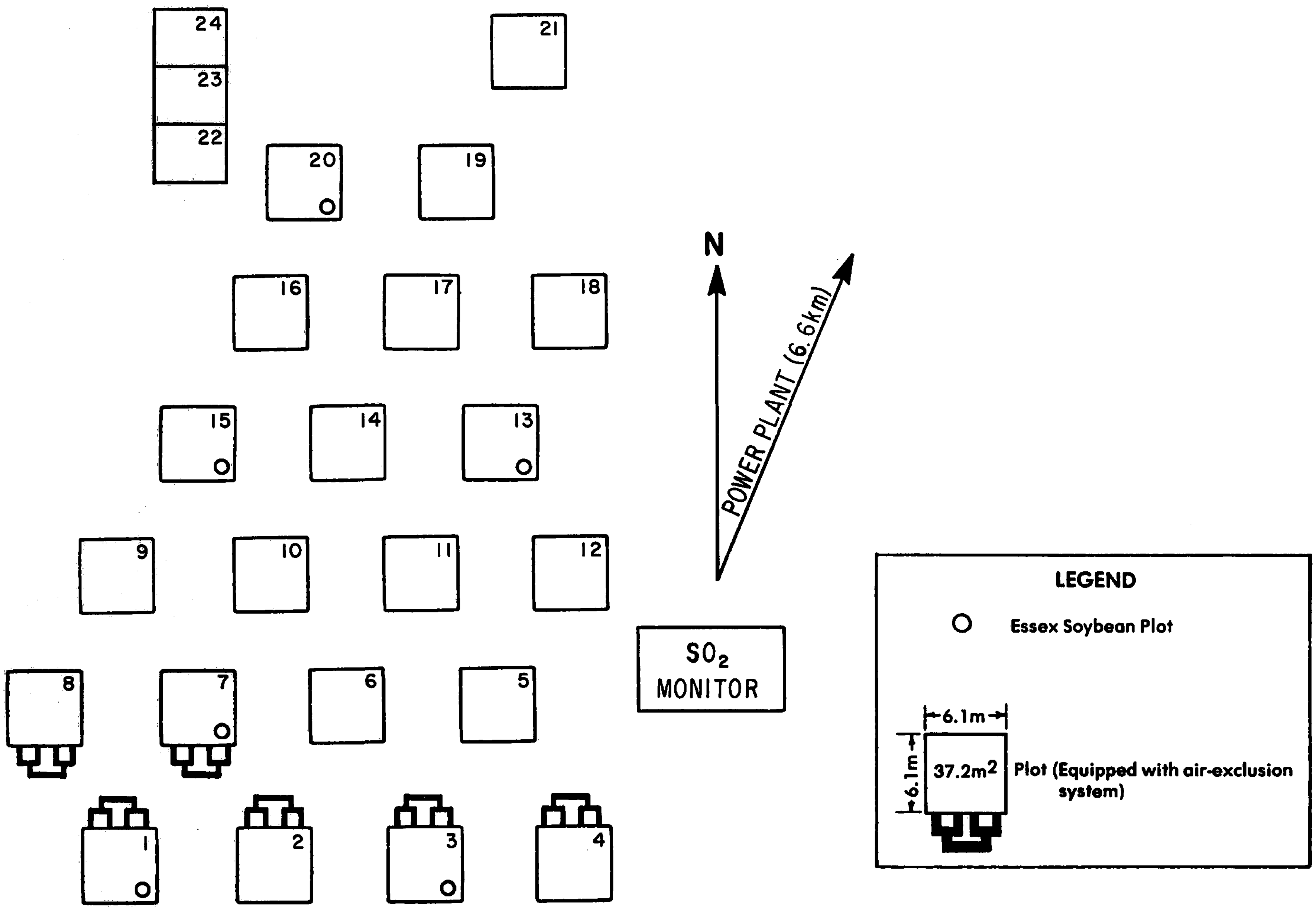

Figure A4. Plot arrangement, monitor 19.

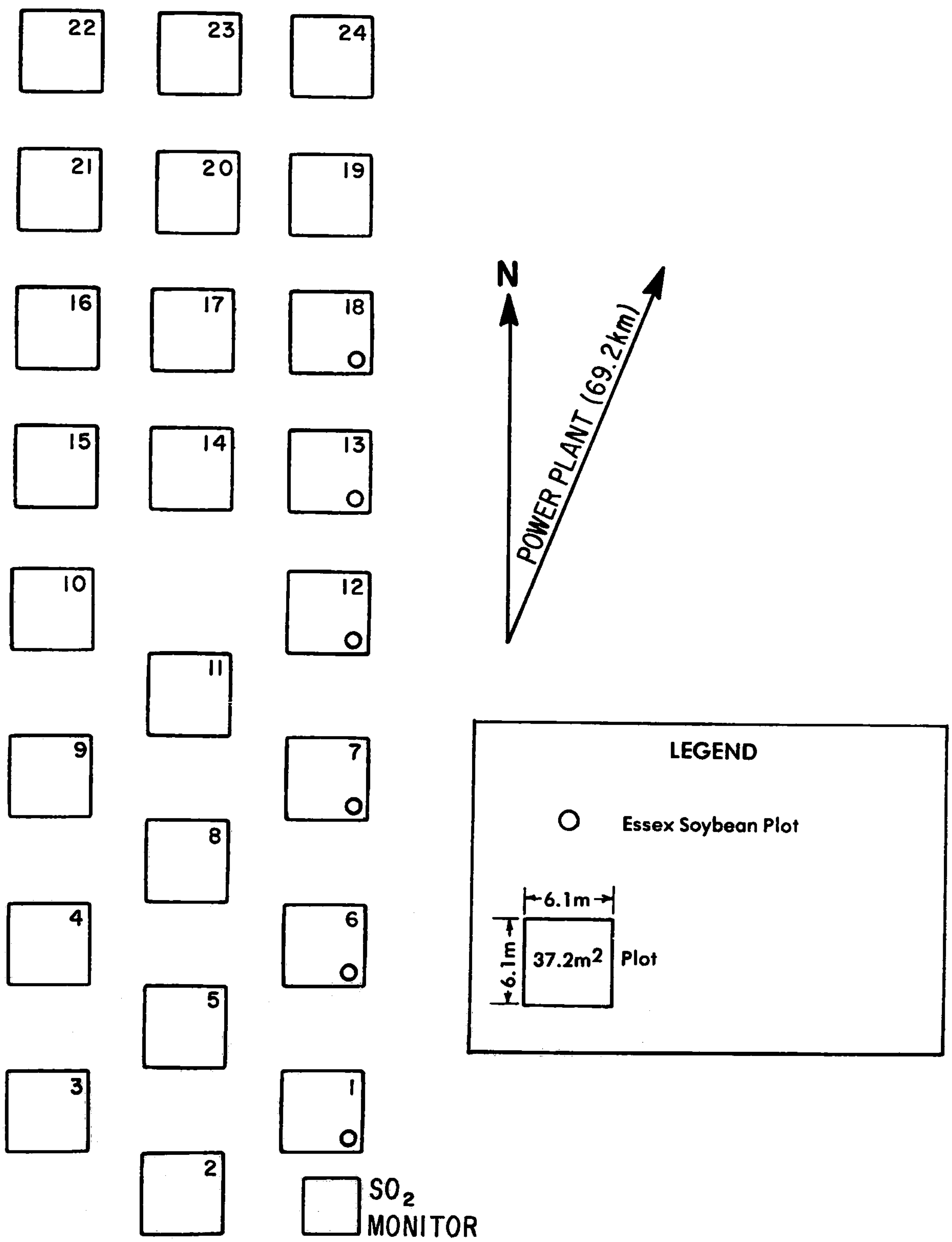

Figure A5. Plot arrangement, monitor 22.

APPENDIX B

SOIL CHARACTERISTICS, AVERAGE SEASONAL PRECIPITATION, AND TEMPERATURE

JACKSON COUNTY[1]

The soils at monitors 6, 9, and 10 are of the Hartsells fine sandy loam type of the eroded, undulating phase. Most of this type of soil occurs in relatively small areas in close association with other Hartsells soils. The soil is similar to the undulating phase, but is more eroded. One-fourth to three-fourths of the original surface soil has been eroded. Both external and internal drainage are good to excellent. The soil has good moisture-absorbing and moisture-holding qualities and good tilth. It is well suited to a wide range of crops and produces excellent yields under good management. Sandstone is found at a depth of 35 to 75 cm. The expected average annual yield per hectare under improved management practices are 4.4 metric tons of soybean hay and 544 kg of lint cotton.

The soil at monitor 19 is of the Hanceville fine sandy loam type of the eroded rolling phase. This type of soil occurs in scattered areas on Sand Mountain. It is closely associated with Hartsells soils and resembles them in texture and friability. However, it has a browner surface soil and red subsoil. It is derived from weathered products of sandstone and, in places, slate. One-half to three-fourths of the original surface soil has been eroded. It has a 10- to 12.5-cm brown, fine sandy loam surface soil and a red, friable, fine sandy clay subsoil. In places plowing brings subsoil material to the surface. However, despite erosion, the productivity of this soil has not been seriously impaired. It is very responsive to good management, and the loose, deep subsoil absorbs and retains moisture well. The expected average annual yield per hectare under improved management practices are 4.2 metric tons of soybean hay and 390 kg of lint cotton.

The seasonal average precipitation and temperature for the growing season for Jackson County are presented in Table B.1.

TABLE B.1. SEASONAL AVERAGE PRECIPITATION AND TEMPERATURE FOR JACKSON COUNTY

Season	Precipitation (cm)	Temperature (°C)
Spring	37.5	15.5
Summer	35	19.4
Fall	22.5	15.4

1. From: Soil Survey - Jackson County, Alabama, Series 1941, No. 8. Issued 1954. U.S. Dept. of Agriculture, Soil Conservation Service, Alabama Dept. of Agriculture and Industry, Alabama Agricultural Experiment Station. U.S. Government Printing Office, Washington, DC. 222 pp.

DEKALB COUNTY[1]

The soils at monitor 22 are in Hartsells fine sandy loam of the eroded, undulating phase. With this type of soil, runoff is slow, and internal drainage is rapid. The moisture-holding capacity is moderate. This soil has been under cultivation for a number of years. Because the surface soil and subsoil materials are friable, the plow layers differ very little from the original surface soil. The depth to bedrock ranges from 0.91 to 1.5 m. When dry, the plow layer varies from light gray to very pale brown. The soil has very good to excellent workability, excellent tilth, and very good moisture-absorbing qualities. The expected average yields per hectare under improved management practices are 6.7 metric tons of soybean hay and 705 kg of lint cotton. The seasonal average precipitation and temperature for the growing seasons for DeKalb County are presented in Table B.2.

TABLE B.2. SEASONAL AVERAGE PRECIPITATION AND TEMPERATURE FOR DEKALB COUNTY

Season	Precipitation (cm)	Temperature (°C)
Spring	37.6	14.9
Summer	35.0	24.6
Fall	22.5	15.2

1. From: Soil Survey - DeKalb County, Alabama, Series 1951, No. 3. Sept. 1958. U.S. Dept. of Agriculture, Soil Conservation Service, Alabama Dept. of Agriculture and Industry, Alabama Agricultural Experiment Station, U.S. Government Printing Office, Washington, DC. 108 pp.

APPENDIX C

PERCENTAGE ORGANIC MATTER, pH, AND CONTENTS OF P, K, Mg, AND Ca OF THE SOILS OF THE EXPERIMENTAL SITES

Monitor No.	Plot No.	pH	Organic matter (%)	Phosphorus (kg/ha)	Potassium (kg/ha)	Magnesium (kg/ha)	Calcium (kg/ha)
6	1	6.4	1.46	85	221	254	1455
	2	5.6	1.86	137	203	159	1120
	3	6.0	2.24	120	222	141	1670
	4	6.2	2.44	117	271	132	1890
	5	6.3	2.92	162	304	163	2250
	6	6.0	2.85	129	273	177	2070
	7	6.2	2.99	121	268	495	3100
	8	6.0	3.33	136	285	181	2340
	9	4.9	2.37	57	240	121	1545
	10	5.2	2.28	98	229	117	1224
	11	5.2	1.80	117	211	106	1189
	12	5.4	1.58	124	204	187	1358
	13	5.2	1.88	132	190	47	876
	14	5.5	2.06	179	228	122	1050
	15	6.0	1.36	91	164	185	1670
	16	6.7	1.64	90	176	167	2380
	17	6.1	2.16	162	208	192	1555
	18	6.2	2.44	163	238	186	1980
	19	5.9	2.68	141	264	198	1890
	20	5.3	2.15	144	192	132	1825
	21	6.3	3.12	212	358	193	2660
	22	5.0	2.14	78	191	103	1568
	23	5.6	2.55	129	239	144	1776
	24	6.0	3.16	152	284	185	1970
9	1	6.4	1.64	92	119	336	2443
	2	6.6	1.98	130	104	30	2480
	3	6.3	2.40	188	181	42	2450
	4	6.4	2.23	164	192	42	2390
	5	6.0	1.76	330	181	39	2252
	6	6.5	1.61	336	228	52	2410
	7	6.0	1.79	400	200	41	1890
	8	5.9	2.20	420	292	49	2080
	9	6.2	1.98	205	181	39	2360
	10	5.4	1.84	285	170	36	2340
	11	6.3	1.72	375	234	38	2162
	12	6.7	1.50	316	262	62	2420
	13	6.7	1.50	318	263	62	2420
	14	6.5	1.90	288	298	73	2387
	15	5.6	2.08	292	223	41	1950
	16	6.1	1.83	281	167	36	2320
	17	6.1	1.40	228	169	36	2342
	18	6.7	1.43	354	181	43	2285
	19	5.9	1.92	100	273	49	1640

APPENDIX C
(Continued)

Monitor No.	Plot No.	pH	Organic matter (%)	Phosphorus (kg/ha)	Potassium (kg/ha)	Magnesium (kg/ha)	Calcium (kg/ha)
	20	5.4	2.47	104	176	61	1195
	21	5.8	1.82	79	144	29	1610
	22	5.9	1.54	66	140	28	1390
	23	6.0	1.54	62	144	28	1493
	24	6.0	1.58	127	208	215	2690
10	1	6.2	1.78	246	232	228	1279
	2	6.1	1.47	169	212	198	920
	3	5.4	1.30	121	172	110	710
	4	4.8	1.61	148	183	49	528
	5	4.8	1.42	115	170	29	450
	6	4.8	1.59	152	194	26	406
	7	5.3	1.43	270	252	83	580
	8	6.0	1.61	222	212	42	2442
	9	6.0	1.82	248	250	35	1850
	10	6.0	1.78	190	234	52	1955
	11	6.0	1.72	137	220	39	2085
	12	6.3	1.96	272	310	53	1580
	13	6.2	1.65	224	255	67	775
	14	6.1	1.60	163	196	105	620
	15	5.9	1.74	168	278	93	1025
	16	6.5	1.65	176	258	64	1195
	17	5.9	1.50	143	184	200	813
	18	6.1	1.57	158	252	215	1165
	19	6.1	1.61	93	190	209	1232
	20	5.4	2.07	172	308	135	835
	21	6.1	1.75	147	203	25	1300
	22	5.8	1.78	174	220	144	850
	23	5.5	1.68	160	208	116	718
	24	5.6	2.20	112	270	122	890
22	1	6.1	0.96	71	244	54	745
	2	6.2	1.17	54	204	70	1050
	3	6.1	0.96	75	215	71	987
	4	6.1	0.98	105	275	85	1230
	5	5.9	0.89	64	226	71	962
	6	5.9	0.92	76	250	52	675
	7	5.7	1.04	71	242	49	684
	8	6.0	1.27	103	347	106	1436
	9	6.0	0.98	109	378	78	1525
	10	6.2	0.83	90	214	53	883
	11	5.9	1.03	122	415	103	1600
	12	5.9	1.03	82	228	47	693
	13	5.7	1.03	79	208	40	613
	14	6.0	1.13	74	202	55	870
	15	6.1	1.01	83	215	53	824

APPENDIX C
(Continued)

Monitor No.	Plot No.	pH	Organic matter (%)	Phosphorus (kg/ha)	Potassium (kg/ha)	Magnesium (kg/ha)	Calcium (kg/ha)
	15	6.1	1.01	83	215	53	824
	16	6.0	1.03	62	225	66	789
	17	5.9	1.03	93	225	52	736
	18	5.8	0.89	67	188	49	738
	19	5.6	1.20	74	206	49	675
	20	5.7	1.24	28	229	48	774
	21	5.9	1.20	81	230	63	833
	22	6.1	1.00	92	240	70	885
	23	5.6	1.00	69	222	43	701
	24	5.7	1.20	62	195	42	566

APPENDIX D

LIST OF EQUIPMENT AND VENDORS

1.	Anemometer	Belfort Instrument Co. Baltimore, Maryland
2.	Charcoal	Barneby-Cheney Columbus, Ohio
3.	Chemiluminescent Ozone Monitor	McMillan Electronics Corp. Houston, Texas
4.	Dayton Wheel Blowers	W. W. Grainger, Inc. Birmingham, Alabama
5.	Dyna Fog Smoke Generator	Westfield, Indiana
6.	Krene Plastic Tubes	Livingstone Coating Co. Charlotte, North Carolina
7.	Sulfur Gas Analyzer, Model SA 160-S	Meloy Laboratories, Inc. Springfield, Virginia
8.	Philips SO_2 Monitor, Model PW9700	Phillips Electronics Instruments, Inc. Mount Vernon, New York

APPENDIX E

PLANTING AND HARVESTING DATES FOR SOYBEANS DURING 1976

Monitor	Planting date	Harvesting date
6	5/27	10/21, 10/22
9	5/26	10/19, 10/21
10	5/26	10/27, 10/28, 11/3
19	5/27	11/4
22	5/27	10/18

APPENDIX F

DEPTH TO BEDROCK, AVERAGE RELATIVE ELEVATION, AND PERCENT SLOPE OF PLOTS AT EXPERIMENTAL SITES

Plot No.	Monitor 6			Monitor 9			Monitor 10			Monitor 22			Monitor 25		
	Depth to bedrock (cm)[a]	Avg. relative elev. (cm)[b]	Slope (%)	Depth to bedrock (cm)[a]	Avg. relative elev. (cm)[b]	Slope (%)	Depth to bedrock (cm)[a]	Avg. relative elev. (cm)[b]	Slope (%)	Depth to bedrock (cm)[a]	Avg. relative elev. (cm)[b]	Slope (%)	Depth to bedrock (cm)[a]	Avg. relative elev. (cm)[b]	Slope (%)
1	63	265	2.85	67	88	3.95	80	188	2.65	68	122	0.20	88	82	2.46
2	55	279	0.25	85	96	1.15	78	207	1.60	67	116	0.00	>90	85	0.08
3	58	268	3.30	87	99	4.50	67	235	2.05	67	124	0.15	87	101	0.79
4	68	250	6.20	>90	98	1.30	82	259	1.90	75	136	0.40	88	111	1.54
5	63	246	4.45	87	101	3.20	77	296	3.15	67	125	0.20	>90	102	1.87
6	66	236	4.20	78	87	1.45	72	270	0.55	80	134	0.55	77	107	2.64
7	60	220	4.10	>90	120	6.30	77	238	2.00	78	151	0.55	77	119	1.87
8	52	195	5.20	>90	139	4.60	82	215	1.55	77	136	0.70	82	125	1.58
9	78	185	3.10	82	128	2.00	77	188	0.50	87	139	0.90	77	136	2.00
10	33	159	1.10	>90	122	4.30	65	212	10.30	77	153	1.65	>90	159	1.75
11	70	133	1.75	87	130	2.35	67	185	4.10	77	145	0.65	80	153	2.25
12	56	104	2.65	87	159	3.45	67	181	0.60	>90	168	0.35	77	156	3.25
13	60	302	3.05	>90	162	3.90	78	212	0.70	82	186	1.05	82	136	5.92
14	45	236	2.55	>90	177	0.30	80	244	0.05	77	180	0.95	83	110	1.62
15	55	224	3.75	>90	180	3.30	<90	229	0.95	73	171	2.60	68	110	1.53
16	72	201	2.90	>90	177	3.60	82	204	0.90	78	197	1.45	77	134	1.82
17	46	197	4.50	>90	174	3.95	82	185	1.60	73	186	3.95	83	130	1.91
18	78	195	4.65	82	185	3.30	77	180	0.35	>90	203	1.30	77	125	1.04
19	55	183	4.30	>90	192	0.10	88	171	1.85	87	220	0.95	82	151	2.04
20	65	169	4.30	88	209	0.60	70	218	1.60	77	217	0.10	75	162	2.16
21	70	151	4.50	>90	218	0.65	80	204	0.65	88	210	2.95	78	168	2.88
22	76	133	5.00	85	212	0.65	62	192	1.20	70	214	4.10	88	194	2.12
23	60	105	3.25	>90	209	0.65	68	197	3.65	83	227	0.50	>90	183	2.58
24	86	73	3.85	>90	221	1.85	80	198	1.35	87	226	2.90	>90	174	1.21

a. Average of three measurements per plot.
b. Average elevation of front and rear of plot.

APPENDIX G

SULFUR DIOXIDE EXPOSURES AND ESTIMATED PERCENT FOLIAR CHLOROSIS FOR THE 1976 GROWING SEASON

Site	Date	SO_2 concentration ($\mu g/m^3$)		Treatment[a]	Estimated chlorosis (%)		
		1-h	3-h		Min	Max	Avg
6	8/13[b]	2351	1463	1	0	8.5	0.9
	8/16[b]	1881	914	2	0.6	30.0	6.4
	8/21	1332	914		No new effects observed		
	9/17	2743	2090		No estimates available		
9	7/22	1097	784		No effects observed		
	8/21	1515	1097	1	0	3.8	0.7
				2	0	7.5	0.7
	9/21	862	784		No estimates available		
10	7/7	1646	1149		No effects observed		
	7/28	1776	993		No effects observed		
	8/14	2194	1515	1	0	4.0	0.5
				2	0.1	0.8	0.3
				3	0.1	4.2	1.0
	8/21	444	340		No new effects observed		
19	7/7	993	836		No effects observed		
	7/10	2482	1228		No effects observed		
	7/14	2142	1541		No effects observed		
	7/23	914	862		No effects observed		
	7/24	10318	4519		No effects observed		
	8/16	1881	888	1	0.2	3.8	1.4
				2	0	3.0	1.0
	8/22	2377	1593	1	0.1	1.8	0.8
				2	0	4.5	0.6
	9/15	1881	1071		No estimates available		

a. 1 - air-exclusion; 2 - exposed with plastic between rows; 3 - exposed without plastic between rows.
b. Observations made on 8/17.

APPENDIX H

YIELDS FOR EXPERIMENTAL PLOTS, 1976 GROWING SEASON, WIDOWS CREEK STEAM PLANT

	Air-exclusion			Exposed (plastic)			Exposed (no plastic)		
Site	Plot	Yield[a] (kg/ha)	Standard deviation	Plot	Yield[a] (kg/ha)	Standard deviation	Plot	Yield[a] (kg/ha)	Standard deviation
6	1	3136	114	13	2821	118	9	2745	99
	2	3359	399	15	2955	513	20	3080	88
	3	3387	102	16	2867	97	22	2883	102
	$\bar{X}$	3294	112		2881	56		2903	137
9	1	3103	108	15	3239	328	10	3380	155
	2	3015	166	13	2597	136	16	3344	259
	7	2901	290	14	2894	286	17	3235	33
	$\bar{X}$	3006	83		2910	262		3320	62
10	1	3610	95	17	3442	223	4	2912	100
	2	3733	151	18	3490	245	5	2628	65
	3	3501	30	19	3682	140	6	2689	37
	$\bar{X}$	3615	95		3538	104		2743	122
19	1	3153	134	13	1393	533			
	3	2917	346	15	767	35			
	7	3291	91	20	1286	41			
	$\bar{X}$	3120	154		1149	273			
22	1	2850	245	12	2703	378			
	6	2673	165	13	2301	144			
	7	2599	92	18	2657	178			
	$\bar{X}$	2707	105		2554	180			

a. Average of yields of three inner rows of plot.

APPENDIX I

DATA SET USED IN REGRESSION ANALYSIS

Site	Plot	Type[a]	Yield (kg/ha)	P (kg/ha)	K (kg/ha)	Mg (kg/ha)	Ca (kg/ha)	pH	OM[b] (%)	IND[c]
6	1	1	3136	85	221	226	1457	6.4	1.46	245
	2	1	3359	137	206	159	1110	5.6	1.86	236
	3	1	3387	120	222	141	1666	6.0	2.24	246
	13	2	2821	132	191	47	876	5.2	1.88	249
	15	2	2955	91	164	185	1666	6.0	1.36	230
	16	2	2867	90	176	167	2369	6.7	1.64	244
	9	3	2745	57	241	121	1545	4.9	2.37	258
	20	3	3080	114	193	132	1831	5.3	2.15	281
	22	3	2883	78	192	103	1571	5.0	2.14	283
9	1	1	3103	92	119	34	2447	6.4	1.64	246
	2	1	3015	130	104	30	2482	6.6	1.98	238
	7	1	2901	400	201	41	1891	6.0	1.79	254
	15	2	3239	293	223	41	1952	5.6	2.08	259
	13	2	2596	317	262	62	2421	6.7	1.50	273
	14	2	2894	288	298	73	2394	6.5	1.90	266
	10	3	3380	252	170	36	2343	5.4	1.84	254
	16	3	3344	291	167	36	2325	6.1	1.83	255
	17	3	3235	229	169	36	2273	6.1	1.40	268
10	1	1	3610	245	232	229	1293	6.2	1.78	207
	2	1	3733	169	212	198	919	6.1	1.47	206
	3	1	3502	121	173	110	711	5.4	1.30	203
	4	3	2912	148	183	49	529	4.8	1.61	169
	5	3	2628	115	169	29	451	4.8	1.42	172
	6	3	2689	152	194	26	407	4.8	1.59	169
	17	2	3442	143	184	201	815	5.9	1.50	222
	18	2	3490	158	252	215	1171	6.1	1.57	213
	19	2	3623	93	191	210	1232	6.1	1.61	207

a. 1 - air-exclusion; 2 - exposed with plastic between rows; 3 - exposed without plastic.
b. Percent organic matter.
c. Index of insect-disease injury.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-77-122	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Experimental Air Exclusion System for Field Studies of SO_2 Effects on Crop Productivity		5. REPORT DATE November 1977 issuing date
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) H.C. Jones, N.L. Lacasse, W.S. Liggett, and Frances Weatherford		8. PERFORMING ORGANIZATION REPORT NO. E-EP-77-5
9. PERFORMING ORGANIZATION NAME AND ADDRESS Division of Environmental Planning, Tennessee Valley Authority, Chattanooga, TN 37401		10. PROGRAM ELEMENT NO. 1NE625B
		11. CONTRACT/GRANT NO. 79 BDL
12. SPONSORING AGENCY NAME AND ADDRESS Office of Energy, Minerals, & Industry, Office of Research & Development, U.S. Environmental Protection Agency, Washington, DC 20460		13. TYPE OF REPORT AND PERIOD COVERED Milestone
		14. SPONSORING AGENCY CODE EPA/600/17

15. SUPPLEMENTARY NOTES

This project is part of the EPA-planned and coordinated Federal Interagency Energy/Environment R&D Program.

16. ABSTRACT

The Tennessee Valley Authority (TVA) characterized and quantified relationships among sulfur dioxide (SO_2) exposure, symptomatology of injury, and yield of soybean crops, which are sensitive to SO_2 and economically important to the southeastern United States. Characterization included analysis of soil fertility, pH, soil depth, slope, and content of organic matter. Regression analysis was used to identify site factors that might affect yield and mask the effects of SO_2 exposure; results of the analyses were used to control or eliminate those factors.

TVA designed, constructed, and tested an air-exclusion system that permits the comparison of plants exposed to SO_2 with plants at the same site that were protected from SO_2 exposure. Tests showed the system to be as much as 85 percent efficient in excluding or reducing SO_2 concentrations to subthreshold levels during exposure.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Ecology Environments Earth atmosphere	Control technology: energy resource extraction Coal cleaning Fuel: Coal	6F; 10A; 10B; 97A; 97B

18. DISTRIBUTION STATEMENT RELEASE UNLIMITED	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES
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