SPAR Overview

SPAR Facility

The Soil-Plant-Atmosphere-Research (SPAR) facility consisting of 10 naturally-lit chambers (Figure 1) located on the North Farm part of the Department of Plant and Soil Sciences, Mississippi State University. The mission of the facility is to provide process-level quantitative data that can be used to understand environmental control of plant growth and development and to quantify crop growth rates for simulation modeling. The data acquisition and control system is composed of six Agilent 34970A data acquisition/Switch units, each with 60 channel measuring capacity (Figure 2) and a John Fluke Model 1120A digital input system connected via an IEEE-488 interface to a desktop computer used as the system controller. The components are networked to provide automatic acquisition of 500 pieces of information from the SPAR units, control of the SPAR environments, and storage of collected data in an on-line data warehouse every 15 minutes, 24 hours a day, during the experimental period, using more than 200 sensors and instruments. This system also provides for automatic error checking and preliminary analysis of collected data on a daily basis. These chambers are uniquely useful for studying canopy and ecosystem or small-plot responses to several combinations of variables in field-like controlled environments. These capacities allow simultaneous determination of several plant responses (e.g., canopy photosynthesis, respiration, transpiration, tissue temperatures, growth and development of organs) under precisely controlled conditions (e.g., temperatures from 10 to 45 °C, CO2 concentrations from 250 to 1000 ppm, ultraviolet-B radiation from 0 to several times of the ambient levels, ability to manipulate water supply and nutrient concentrations through a set of sensors and program algorithms). The gas-exchange processes and many soil and aerial environmental conditions are measured and/or adjusted on a 10-s basis in each SPAR unit. Also, the 1-m deep soil bin of the SPAR with rooting medium known as minirhizotron (Figure 3) provides an opportunity to study the root growth nondestructively during the experiment. This facility will also allow the study of several other biotic (e.g., weeds, insects, diseases) and physical environmental conditions. Adjacent to the SPAR facility, an outdoor Pot-culture facility (about 2000 pots; Figure 4) with computer-controlled nutrient and irrigation capabilities is uniquely suited for studying crop growth and developmental processes responses to nutrient and water regimes. Recently, remote sensing techniques are being used at this facility to develop reflectance signatures and spectral algorithms for abiotic stresses The SPAR facility offers training experience for part-time students, undergraduate and graduate students, and post-doctoral scientists in whole plant and environmental plant physiology including global climate change effects. Tours are provided for schools and community groups as well.

SPAR Physical Description

The SPAR units are located outdoors on a 20x30 m concrete pad (Figure 1). Each unit has the capability for controlling air temperatures, and atmospheric composition (especially CO2 concentration) at predetermined set points for studies of plant growth in natural solar radiation regimes. The bottom third of each SPAR unit consists of a steel bin to contain rooting medium. The upper two-thirds is an airtight Plexiglas chamber of 2.5 m high and 2.0 x 1.5 m in cross-section to accommodate the aerial plant parts (Figure 3). A door in the bottom of the aerial portion of each chamber (Figure 4) is hinged for access to the soil surface and the aboveground portions of the plants (Figure 5). Ducts on the northern face connect to the cooling system (Figure 6). Conditioned air is introduced at the top of the Plexiglas chamber, flows down through the plant canopy, and is returned to ducts just above the soil surface. A steel soil bin contains the rooting medium, and measures 1.0 m deep x 2.0 m long x 0.5 m wide (Figure 7). The northern face of the soil bin has many large holes closed with rubber stoppers to facilitate measuring soil environmental conditions (Figure 8). The southern face is constructed of reinforced glass to allow collection of data on root growth dynamics (Figure 3). The plants in the SPAR units receive natural solar radiation (94% transmisive to photosynthetically active radiation) and have capabilities for controlling both the aerial and soil environment across a wide range of environmental set points. Factors controlled include atmospheric carbon dioxide concentration, dry-bulb air temperature, and dew point temperature. The environmental control system can be programmed to provide continuously changing values over a diurnal cycle to yield either a smooth sinusoidal or a square wave fashion. Similarly, a monitoring system provides accurate measurement of the environmental conditions throughout an experiment. Set points also can be programmed to change for short-term periods so that plant responses to short-term environmental conditions can be investigated during critical stages of crop development. In addition, [CO2] can be maintained from subambient to superambient levels in the SPAR system in a manner not possible with other types of field exposure systems. This capacity allows investigation of specific processes related to reduced carbon sources and sinks and their interactions that lead to a widely varying growth, development, and fruiting patterns in crops. Because the SPAR units provide continuous measurement of canopy photosynthesis, respiration and transpiration throughout the experimental period, these biophysical processes can be determined under precisely controlled conditions. From these results, rate equations can be developed for building new mechanistic crop simulation models of growth and development and/or improving the existing models.

Spar Temperature Measurement and Control

The air temperature is monitored and adjusted automatically every 10 s throughout the day and night. Control of the air temperature is maintained using a dedicated computer (Figure 9) that opens and closes a set of solenoid valves (Figure 10) to a chilled water radiator and switches a heating system on

and off. Heat is provided by two 11 kilowatt heating elements (Figure 11) mounted on either side of the air circulation unit. Air temperature is monitored using an aspirated, shielded thermocouple (Figure 12) and maintained within + 0.5oC of the treatment set points over a daytime range of 18EC to 40EC and a nighttime range of 12EC to 32EC. The dew point temperatures are measured, but not controlled, with a gold mirror hygrometer (Figure 13, Model Dew-10, General Eastern Instruments, Woburn, Massachusetts, USA) installed inside the return airline. Figure 14 illustrates typical air temperature control during one day. The dew point temperatures are collected at 10-s intervals and summarized over 900-s periods. Constant humidity is maintained by operating solenoid valves that injects chilled water through the cooling coils located in the air handler of each SPAR chamber. The cooling coils condense excess water vapor from the chamber air in order to regulate relative humidity at approximately 55 to 60% (McKinion and Hodges, 1985). Figure 15 illustrates typical dew point temperature measurement during one day for plants grown at a range of air temperatures. Canopy temperature of plants is also monitored every 10 s using infrared thermometers (Figure 16, Model 400AT, Everest Interscience Inc., Tucson, Arizona, USA) and the values averaged over 900-s intervals throughout the experimental period.

Examples of Crop Responses to High Temperatures : High Temperature Injury in Cotton Fruit

The SPAR facility is highly effective in studying the influence of high temperature on crop fruit production efficiency and other reproductive related processes. Figures36 and 37 illustrates the effect of high-temperature injury on cotton fruit retention, as factors other than temperatures were eliminated as uncontrolled variables. The mechanisms causing reproductive failure at high temperatures are still not known, but the consequences are clear and quantifiable. When plants were grown at 40°C, we observed injury to the developing ovules up to 12 days before pollination. Pollen was also damaged when plants were at 40EC during development. Because, selection for heat-tolerant genotypes is an objective in both traditional breeding and biotechnology research programs, temperature-responses are certainly an area of research that needs further and more extensive study in many crops.

Spar Carbondioxide Measurement and Control

Similar to temperature control, the [CO2] in each SPAR unit is also monitored and adjusted every 10 s throughout the day and is maintained within 10 µL L-1 of treatment set points during the daylight hours by adjustment of controls consisting of a set of pressure regulator, calibrated rotometer, needle valve and solenoid valves. A mass-balance approach based on an output from a dedicated CO2 analyzer for each unit (Figure 16, Model, LI 6200, LI-COR Inc., Lincoln, Nebraska, USA) is used to open and close the solenoid valves as needed to maintain a constant atmospheric {CO2] in each unit Gas sample lines for

measuring chamber and ambient air carbon dioxide are being drawn through the lines that run underground from SPAR units to the field laboratory building. Moisture is removed from the gas sample by running the sample lines through refrigerated water tap (4 °C) that was automatically drained once an hour (Figure 17) and through a column of magnesium perchlorate (Figure 18). The chamber carbon dioxide is maintained by supplying pure carbon dioxide from a compressed gas cylinder through a system that includes a pressure regulator, solenoid valve and needle valves and a calibrated flow meter (Figure 19; Reddy et al., 2001). The flowmeters are calibrated with a gas displacement instrument (Figure 20) at the beginning and end of each experiment. Figure 21 illustrates typical carbon dioxide control during one day.

Photosynthesis and Respiration Measurement

Each SPAR unit=s growth chamber and fan-coil box form a semi-closed system for the measurement of canopy CO2 and water vapor exchange (Figure 4). The Plexiglas chamber containing the plants, ducts, and cooling system is nearly airtight. A mass balance approach is used to calculate net CO2 exchange rates (Pn) of the plant canopies throughout the experiment. Precise control of the [CO2] at + 10 µL L-1 of the treatment-set point is achieved by using an absolute infrared gas analyzer (LI-COR Inc., NE, USA), calibrated weekly, automatically correcting CO2 analyzers dedicated to monitor each unit for calibration drift every 900s. Carbon dioxide flow rates are recorded three times a day and converted into mass quantity via gas law correction for temperature and pressure. The time intervals during which the solenoid valves are open are monitored by a computer, and thus the amount of CO2 injected is known. A leakage test is performed each night to derive the plant growth chamber leakage rate and to correct canopy gas measurements. Using values for the mass of CO2 injected to maintain treatment-set point, and the mass of CO2 lost via leakage, one can calculate net canopy photosynthesis per unit ground area, Pn (mg CO2 m-2 s-1). Rates of CO2 fixation for cotton at a full canopy are shown for a typical diurnal cycle (Figure 22 and 23), and are closely coupled to the amount of solar radiation received. In chambers with 720 µL L-1 [CO2], the maximum rates were about 6 mg CO2 m-2 s-1, while the maximum rates in plants at ambient [CO2] about 4 mg CO2 m-2 s-1. "Dark" respiration rates (mg CO2 m-2 s-1) are calculated in a similar manner by maintaining daytime temperatures one hour into the nighttime period. Consequently, gross canopy C exchange rate, Pg, is calculated and used to correct Pn data for daytime "dark" respiration rates. We have routinely used these data to quantify the photon flux density vs. Pn or Pg of cotton canopies, and have found a close relationship (r2 = 0.97) between seasonal Pn and biomass.

Examples of Canopy Photosynthesis : Gas Exchange Measurements

Using mass-balance approach as described under Carbon Dioxide Control and Measurement section, canopy photosynthesis can be measured throughout the

day and can be expressed as a function of photosynthetically active solar radiation and [CO2] (Figure 27). In this example, the measurements were taken when the canopy was closed, intercepting about 95% of the incoming solar radiation during fruiting period in cotton. Plants were grown in optimum temperature, water, and nutrient conditions, but in varying CO2 environments. Unlike data obtained in indoor, light-limited plant growth chambers, cotton canopy photosynthetic rates did not appear to be light-saturated even at high radiation levels in present-day [CO2] environments. Doubling [CO2] in the atmosphere increased both the initial slope of the diurnal light response curve and the estimated maximum light-saturated rate. Using the SPAR system, the initial slopes and the maximum rates can be generated from the canopy light response curves as functions of various temperature, atmospheric [CO2], water, and nutrient regimes by manipulating these environmental conditions. From these physiological response functions, and knowledge of canopy light interception, it is possible to develop a functional model of canopy carbon exchange rates for field-grown crops. From light response curves of the type depicted in Figure 28, the daily net photosynthetic rates at a specific radiation level can be estimated and the values plotted throughout the growing season to compare environmental conditions (e.g., Figure 29). Under ambient temperature of 30°C and atmospheric [CO2] of 350 µL L-1 CO2, the maximum photosynthetic rate at 1200 µmol mol-1 s-1 PPFD was reached about 30 days after flowering, and then gradually decreased as the season progressed. In cotton, fruit-set (boll number) increases rapidly after first flower stage until the size of the fruit load (a major sinks for C) reaches the maximum the plant can support. Actually, the maximum number of fruits that a cotton plant can support varies daily, depending on the amount of photosynthate production, respiration rate, and limitations due to nutrients and water. In cotton, as in most other indeterminate plants, some or all young fruit within a certain maturity class may abscise on certain stressful days, but when conditions improve later an even larger number of fruits might be added and subsequently supported to maturity. It is interesting to find a decrease in canopy photosynthesis in cotton during the important fruit-growth period (Figure 29). Among possible reasons for this decline is a decrease in solar radiation as the season progresses in the midsouthern USA; however, this can be excluded in the present SPAR study because data were normalized to a PPFD of 1200 µmol-2 m-2 s-1. Therefore, one must conclude that radiation-use efficiency decreased in these plants as the season progressed following flowering. Regressing photosynthetic rates as a function of days after emergence (DAE) from DAE 80 to maturity yielded a slope of -0.032 mg CO2 m-2 s-1 d-1 for 360 µmol CO2 mol-1 air and -0.015 mg CO2 m-2 s-1 d-1 for 720 µmol CO2 mol-1 air (Figure 29). The ratio of these diurnal slope values indicates Pn was enhanced about 46% by doubled [CO2], as compared to plants grown in ambient [CO2]. This reflects a 47% greater rate of canopy photosynthesis in plants grown at twice-ambient [CO2] on 80 days after emergence compared to plants grown in ambient [CO2]. The net effect was an approximate doubling (99% increase) of cumulative seasonal net photosynthesis estimated using the regression parameters from each day=s net photosynthesis

values, due to doubling CO2 levels, from 7.25 kg CO2 assimilated in ambient air to 14.49 kg CO2 assimilated in elevated [CO2]. Higher photosynthesis in elevated CO2 environments may be due to both the direct effects of higher [CO2] in the atmosphere and thus a steeper gradient between atmosphere and the chloroplasts and the indirect effects of carbon on sustaining more vegetative growth longer into the fruiting period thus causing a younger canopy of leaves in the high-CO2-grown crop.

Measurement of Canopy Transpiration

Canopy transpiration rates are also measured and are normally expressed on a ground area basis (g H2O m-2 s-1) throughout the growing season. This is measured as the rate at which condensate is removed by the cooling coils at 900-s intervals (Figure 24, McKinion and Hodges, 19985) by measuring the mass of water in collecting devices connected to a calibrated pressure tranducer (Figure 25). The soil surface is sealed from gaseous exchange with the aerial environment using plastic sheeting. Data on diurnal trends in radiation and transpiration for flowering cotton plants grown at two [CO2] for a typical clear day are presented in Figure 26. From measurements of photosynthesis and transpiration, water-use efficiency (g CO2 fixed per unit of water transpired) of crop canopies can be estimated as functions of various environmental conditions.

Examples of Canopy Transpiration Measurements

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Examples of Crop Developmental Rates

Examples of classical growth analysis to determine changes in a developmental rate of a cotton crop are presented in Figs. 30 to 33 for plants grown under favorable water and nutrient conditions. It is practically impossible to obtain such data in field situations, because many physiological and environmental factors vary or interact in complex ways to affect cotton development. Even with suitable control of cultural practices, several experiments are needed from different geographic locations in order to generate valid crop

development data. Using SPAR chambers, it possible to describe the number of days between seedling emergence and first square, and calculate the daily rate of development (reciprocal of days) for this growth process to occur (Figure 30). Similarly, the rate of square (flower-bud) and boll development can be described (Figure 31), as well as phyllochrons for mainstem leaves and fruiting branches, as a function of temperature (Figure 32). These processes are important for understanding growth and development in cotton, and in managing the crop, because it is tropical in origin, and very sensitive ambient temperatures. In a field environment, variability in temperature within and between days makes develop functions for plant phenology nearly impossible, but such functions can be developed in the SPAR units and applied effectively to predict growth and development in the natural world where variables conditions are paramount. Although, one can estimate phenological development by using either hourly or daily developmental rates and either hourly or daily temperatures, the data can be more useful if one calculates the reciprocal of the number of days required to reach an event from the average temperature for each day. These daily reciprocal values can be added together until they total 1.0 or greater. At that time, the phenological event should be observed. Daily average temperature can be estimated by summing the maximum and minimum temperatures and dividing by two. When cotton plants were grown in continuously varying temperatures such as occurs in nature, we observed plants have responses similar to those of plants grown at the same average, but at constant day/night temperature conditions. We have incorporated a number of process-level rate equations and algorithms into the cotton simulation model, GOSSYM and tested the predictive ability of these algorithms using independent data sets that measured plant height, mainstem node numbers, and yield collected across the U.S. Cotton Belt. Because these data sets include 50 cropping systems from 1987 to 1992, they represent a wide range of environmental conditions, cultural practices, and genetic resources. The data sets comprise both irrigated and rain-fed conditions, with three or more cultivars, and with several different soils. The performance statistics for GOSSYM model prove the applicability of the algorithms generated using the SPAR facility (Table 1). One can use similar procedures to develop computer-assisted tools for estimating the time for other developmental events to occur, such as the addition of a new mainstem node that supports a leaf and sympodial branch of a fully expanded leaf. Such an exercise can be readily performed, but using records for dates of planting and emergence and daily temperatures. This calculation allows one to document an almost reasonably quantitative estimate of crop status that is almost independent of location or calendar dates. Water and nutrient deficits seem to have little effect on developmental processes in cotton unless the deficiencies are extreme. However, such deficiencies dramatically affect leaf and stem growth processes and thus alter canopy development. We have found both species and cultivars have different temperature-response functions. For example, the minimum number of days required for two Upland cotton cultivars, DES 119 or DPL 5415, to produce the first square was observed at 28EC (Figure 33). Another Upland

cultivar, DPL 50, required 5 to 8 more days to produce the first square at all temperatures. A Pima cotton cultivar, S-6, had a response for this developmental event nearly equal to that of an Upland cultivar, DES 119, up to 27 to 28EC, but in higher temperatures, Pima development was delayed by about 8 days at 30°C, and 15 days at 35°C compared to DES 119. Pima cultivar, S-6, failed to produce squares if the temperature was above 35EC. This knowledge helps to identify the level of heat tolerance in different species and varieties, and illustrates that certain traits can be selected to fit a niche environment.

Examples of Crop Responses to Specific Deprivations

The SPAR facility also allows one to vary water or nutrients to quantify functional relationships between specific deprivation such as water deficits and nutrient deficits. For an example, the relationship between midday leaf water potential and both canopy net photosynthesis and stem growth in cotton clearly illustrates the effects of a single, well-defined environmental variable on different plant processes (Figure 34). Results demonstrate that stem elongation is more sensitive to water deficits than photosynthesis. The relationships between these two plant processes differ under different environmentally-induced stresses, but they are consistent and predictable. The relationship can be quantified and can be incorporated into a simulation model such as GOSSYM, a cotton simulation model that can aid management decisions. For instance, the relationship between different plant processes may shift under nutrient-stress conditions. In well-fertilized plants, both photosynthesis and leaf expansion proceed at their potential rates; however, in N-deficient environments leaf expansion is reduced more than photosynthesis (Figure35) similar to their responses to midday leaf water potentials.