Cotton Response to CO_2, Water, Nitrogen and Plant Density – A Repository of FACE, AgIIS and FISE Experiment Data

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Abstract: Several cotton experiments have been conducted at the University of Arizona's Maricopa Agricultural Center from which datasets have been obtained documenting cotton responses to elevated CO_2 concentrations, water supply, nitrogen fertilizer, and planting density. In particular, these experiments included FACE (free-air CO_2 enrichment; CO_2, water; 10 treatment-years), AgIIS (Agricultural Irrigation Imaging System, pronounced Ag Eyes; nitrogen fertilizer, water supply; 4 treatment-years), and FISE (FAO-56 Irrigation Scheduling Experiments; irrigation scheduling method, planting density, nitrogen fertilizer; 24 treatment-years). Besides achieving the experimental objectives of determining cotton's response to the several variables, as well as testing remote sensing techniques, the comprehensive datasets are suitable for validating plant growth models because they include weather, soils, management, growth, yield and other data.

Keywords: cotton, CO_2, carbon dioxide, drought, climate change, nutrient, irrigation, irrigation scheduling, crop growth modeling, plant population density, remote sensing.

1 BACKGROUND Concerns about likely effects of the increasing atmospheric CO_2 concentration on managed and natural ecosystems under open-field conditions in the future led to the development of free-air CO_2 enrichment (FACE) technology in the late 1980s on cotton (Gossypium hirsutum L.) near Yazoo City, Mississippi (Hendrey, 1993). Subsequent cotton experiments were conducted from 1989 through 1991 near Maricopa, Arizona with an additional water supply treatment added the latter two years (for a total of 10 treatment-years). Additional FACE experiments were conducted at Maricopa on wheat and sorghum for which datasets have recently been published (Kimball et al. 2017, 2021). The availability of such unique experimental conditions attracted a large team of researchers who measured many aspects of cotton physiology, growth, and yield, as well as soil moisture and water use. Results from the FACE Cotton experiments were published in special issues of Critical Reviews in Plant

Sciences (1992, Vol. 11, Nos. 2-3) and Agricultural and Forest Meteorology (1994, Vol 70, Nos. 1-4). The papers in "Critical Review*"* were also published in a book edited by Hendrey (1993). Details about these many measurements can be found in the comprehensive list of papers in the file called "FACE Cotton Publications.docx". Contained in the dataset described herein are many of the underlying digital data from these first FACE Cotton experiments, including the weather, management, soil properties and water content, phenology, growth, and yield, such as needed for evaluation of cotton growth models.

One goal for remote sensing research in agriculture is to detect the onset of water stress in crops and signal the need for an irrigation. Similarly, another goal is early detection of nitrogen stress and signal a need for fertilization. To meet these goals, an AgIIS (Agricultural Irrigation Imaging System, pronounced Ag Eyes) apparatus was developed (Barnes et al., 2000a,b; Kostrzewski, 2002; Haberland et al., 2010). It consisted of a small cart with many sensors to detect crop temperature and reflectance at many wave lengths remotely. The cart ran back and forth on a small track mounted on top of a linear-move irrigation system as it moved across a field. The system was installed in a cotton field in 1999 near Maricopa, Arizona, which was divided into 16 plots and which received limited and ample water and limited and ample nitrogen for a total of 4 treatment combinations. Besides the many remote sensing measurements with the AgIIS system, like with the FACE experiments, field data were also collected, including weather, management, soil properties and water content, phenology, growth, and yield, such as needed for evaluation of cotton growth models.

A widely used method for scheduling irrigations in arid regions is the so-called FAO-56 method (Allen et al., 1998). It is based on tabulated "crop coefficients", which vary in a prescribed way with days after planting during a growing season. However, it does not account for variations from average in crop growth rates, which can change in response to weather, nitrogen supply, etc. In order to improve irrigation scheduling methodology, FAO-56 Irrigation Scheduling Experiments (FISE) were conducted on cotton in 2002 and 2003 near Maricopa, Arizona, wherein the irrigations for half of the plots were scheduled following FAO-56 and the irrigations for the other half were scheduled using crop coefficients based on measured leaf area during the season (Hunsaker et al., 2005). Leaf area was determined using remote sensing methodology. To test the leaf area methodology, the field was divided into plots with 3 levels of plant density and 2 levels of nitrogen, as well as the 2 scheduling methods for a total of 24 treatment-year combinations. There were 2 or 4 replicates depending on the treatment combination. Like AgIIS, besides the remotely sensed leaf area measurements, there also were observations of weather, management, soil properties and water content, phenology, growth, and yield, such as needed for evaluation of cotton growth models.

The FACE, AgIIS, and FISE experiments were conducted on three different fields located on the University of Arizona's Maricopa Agricultural Center (33.07°N, 111.98°W, elevation of 360 m), and a few of our co-authors participated in all three. Besides the FACE apparatus performance or remote sensing observations, the three experiments included six growing seasons with CO_2, water supply, nitrogen supply, and/or plant density variables. Details about many of these measurements can be found in papers listed in the references and in the file named "FACE Cotton Publications.docx."

As mentioned above, the measurements typically required for evaluation of plant growth models were obtained for all the experiments. Many of these data were assembled by Kimball et al. (1993) and by Thorp et al. (2014). Indeed, Thorp et al. used the data for validation of the CSM-CROPGRO-Cotton model. Herein, all data that could be assembled from these experiments are included for purposes of cotton growth model evaluation along with additional remote sensing data. The modeling data are formatted in the ICASA Version 2.0 format (White et al., 2013) with some modifications under the umbrella of the AgMIP (Agricultural Model Inter-comparison and Improvement Project; http://www.agmip.org/). These data are included in this dataset in files "FACE Cotton Growth Management Soil.ods", "AgIIS Cotton Growth Management Soil.ods", and "FISE Cotton Growth Management Soil.ods"

2 METHODS

2.1 FACE: The free-air CO_2 enrichment (FACE) technique was used to enrich the air of 22-m-diameter circular plots to 550 ppm by volume (Lewin et al., 1992; 1994). Four replicate FACE plots had blowers, toroidal plenums and vertical vent pipes with holes from which pre-diluted CO_2 was released just above the crop canopy. Under computer control, valves at the base of the vent pipes only released the CO_2

on the upwind sides of the plots. The FACE plots were enriched only during daytime. There were four corresponding Control plots with no apparatus in 1989 but with pipes and no blowers in 1990 and 1991. Midday ambient CO_2 concentrations averaged about 370 ppm.

The crops were irrigated using a subsurface drip system (Mauney et al., 1994), with “Wet” plots receiving ample amounts calculated to replace evapotranspiration. In 1990 and 1991, the plots were split, with “Dry” halves receiving 75% and 67% as much water as the Wet halves, respectively.

Recently, Allen et al. (2020) assembled data about the effects of fluctuating CO_2 (such as found in FACE plots) on the growth of C_3 plants like cotton compared to steady CO_2-enrichment. Their conclusions suggest that the responses of C_3 crops in FACE experiments need to be multiplied by a factor of about 1.5 to get the true values for steady enrichment as expected in fields in the future.

2.2 AgIIS: A Latin square experimental design was used to inter-compare four treatments: limited nitrogen and limited water (nw), optimal nitrogen and limited water (Nw), limited nitrogen and optimal water (nW), and optimal nitrogen and optimal water (NW) (Barnes et al., 2000a,b; Kostrzewski et al., 2002). There were 4 replicates of each treatment. A pre-plant nitrogen application was made (34 kg ha^{-1}) to the whole field, and the cotton was planted on 16 April 1999. Four additional nitrogen applications as fertigation were done during the growing season with the limited nitrogen treatment receiving a total of 112 kg N ha^{-1} while the optimal nitrogen plots received a total of 222 kg N ha^{-1}. Soil moisture was measured with a field-calibrated neutron probe and time domain reflectometry (TDR) (Colaizzi et al., 2003), and irrigations were scheduled when the soil water contents were depleted by 30% for the optimal water treatment and 50% for the limited water treatment. The total irrigation amounts were 1000 and 1070 mm for the limited and optimal treatments, respectively, with both getting an additional 150 mm from rainfall.

2.3 FISE: One FISE experiment was conducted during 2002 and a second in 2003 (Hunsaker et al., 2005). There were 32 plots, half of which were irrigated following FAO-56 (Allen et al., 1998) while the other half were irrigated using coefficients based on leaf area as determined from normalized difference vegetation indices (NDVI). The NDVI was calculated from measured crop canopy reflectance in the red and near-infrared (NIR) bands [NDVI = (NIR-red)/(NIR+red)]. A second treatment was plant density (Sparse – 5 plants m^{-2}; Typical – 10 plants m^{-2}; Dense – 20 plants m^{-2}), and a third treatment was nitrogen level (Low and High). There were 4 replicates of all treatment combinations with Typical plant density whereas there were 2 replicates of each treatment combination with Sparse or Dense plant density. Including preplant N application, in-season N applications, and the irrigation water N contribution, the High and Low nitrogen plots in 2002 received a total of approximately 226 to 246 kg N ha^{-1} and 86 to 106 kg N ha^{-1}, respectively, whereas the High and Low plots in 2003 received a total of 162 to 182 kg N ha^{-1} and 50 to 70 kg N ha^{-1}, respectively. Irrigation amounts ranged from 992 to 1122 mm with each treatment receiving a different amount depending on their leaf area development rates. Overall averages of irrigation amounts were 1114 and 1027 mm per season for the FAO-56 and NDVI methods, respectively.

3 DATA FORMAT AND STRUCTURE: The management, weather, growth, and yield data are formatted in the ICASA Version 2.0 format (White et al., 2013), which in turn is undergoing some modifications under the umbrella of the AgMIP (Agricultural Model Inter-comparison and Improvement Project; http://www.agmip.org/). These data are included in this dataset in the files “FACE Cotton Growth Management Soil.ods”, “AgIIS Cotton Growth Management Soil.ods”, and “FISE Cotton Growth Management Soil.ods”. Additional remote sensing data are formatted similarly.

Table 1. Explanatory notes on files

File Name	Content
Weather Maricopa AZMET.ods	Weather data from 1988 through 2003 for Maricopa Agricultural Center from the Arizona Meteorological Network (AZMET).
FACE Cotton Growth Management Soil ET.ods	Main FACE spreadsheet with growth, growth stage, yield, management, soil moisture, evapotranspiration (ET), and other data generally used for plant growth model validation.

Table 1. Explanatory notes on files (Continued)

File Name	Content
FACE Cotton Carbon Isotopes and Tracing.ods	Data on the carbon isotopic composition of the FACE and Control cotton plants and soil, as well as of carbon sequestration in the soil.
FACE Cotton Publications.docx	List of publications stemming from the FACE Cotton Project
AgIIS Cotton Growth Management Soil.ods	Main AgIIS spreadsheet with growth, growth stage, yield, management, and other data generally used for plant growth model validation.
AgIIS Reflectance Soil Moisture ET.ods	Reflectance data and resultant vegetation indices, particularly the Canopy Chlorophyll Content Index (CCCI), as well as soil moisture by depth and time and ET.
AgIIS 1999 Calibration Details.docx	Detailed descriptions of the procedures used to obtain the reflectance data and subsequent vegetation indices.
FISE Cotton Growth Management Soil ET.ods	Main FISE spreadsheet with growth, growth stage, yield, management, soil moisture, ET, and other data generally used for plant growth model validation.
FISE Cotton Midday Canopy Temperatures	FISE cotton canopy or foliage temperatures measured at midday with portable hand-held infrared thermometers.
FISE Cotton Reflectance Factors and Multispectral Vegetation Indices.ods	Cotton canopy and soil reflectance factors measured with a ground-based Exotech Radiometer at a time corresponding to a constant solar zenith angle and used to compute NDVI, CCCI and faPAR

4 ACKNOWLEDGEMENTS: The FACE research was supported by the Carbon Dioxide Research Program of the U.S. Dept. of Energy, Environmental Sciences Division and by the Agricultural Research Service, U.S. Dept. of Agriculture. The FACE apparatus was furnished by Brookhaven National Laboratory, Upton, New York, USA. We acknowledge the untiring cooperation of Dr. Roy Rauschkolb, Dr. Robert Roth, Mr. Pat Murphree, and their staff at the Maricopa Agricultural Center, University of Arizona, Maricopa, Arizona, USA.

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