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GOSSYM Cotton Model: Case Study 18

Research goal	To evaluate the quantitative effects of drought stress on the rate of photosynthesis of cotton plants. To incorporate the information into process-driven dynamic models to aid in cotton crop irrigation management.
Beneficiaries	Cotton growers, crop consultants, researchers in the management of irrigation water, nitrogen, plant growth regulators, and crop termination chemicals.
Activities conducted in order to achieve the objectives	Experiments under controlled environmental conditions, in Soil Plant Atmosphere Research units, on the effect of water stress on leaf senescence and the recovery of the leaf canopy from stress following re-watering.
Funding	BARD award: IS–181-80; $180,000
Publications	1 journal publication
Students involved	2 Ph.D. students. Currently, 1 is in the USDA, ARS – Beltsville and 1 works in the Agricultural extension services in Israel
Stakeholders' collaboration	Extension services, Farm managers, US national Cotton Council
Environmental impact	Informed irrigation and fertilizer application can lead to reduction in water waste and soil-water nitrogen levels.
Social impact	none
Commercial engagement	none
Patents	none
Practical agricultural applications	Use of the GOSSYM model on US commercial farms in 14 US states as a decision support system for determining crop termination, nitrogen utilization, the application of plant growth promoters and irrigation practices in efforts to maximize profit, minimize risk and optimize input. In Israel, the indices and coefficients used to calculate the irrigation schedule, rates and method as a function of measured evapotranspiration/evaporation were linked to plant height and this coefficient methodology is used till today for the cotton crop grown area in Israel.
Economic impact	Net present value of the BARD's investment is $813 million, thereof $813 million already attained The Internal rate of return is 98% Benefit cost ratio is 288, thereof 288 already attained The NPV for the US economy is $766 million The NPV for the Israeli economy is $47 million

1 Objective:

To develop a dynamic process-based simulation model for cotton crop management decision support

For cotton, draught stress and implementation of irrigation scheduling is probably the most important management decision affecting lint yield and quality. The research evaluated the quantitative effects of drought stress on the rate of photosynthesis of cotton plants with the aim of incorporating the findings into GOSSYM, a dynamic, process-based simulation model of cotton growth and yield developed for cotton crop management decision support.

2 Research Activities

BARD award #IS–181-80 was awarded to Avishalom Marani (Hebrew University) and Don Baker (USDA, ARS, Mississippi) for "Development of a Management-Oriented Dynamic Simulation Model for Cotton Production". See Appendix A for full details of the award.

D. Baker studied plant physiological processes such as rates of photosynthesis, respiration, transpiration, growth, and development and connected these processes to solar radiation, temperature, CO_2, soil moisture, solar radiation and nutrient concentrations. Together with J. R. Lambert at Clemson University, he drafted the first version of the GOSSYM predictive model that simulates the basic biological and developmental processes involved in the growth and yield of cotton over a wide range of soils and climate conditions.

GOSSYM includes simulation of the movement of roots, water and nutrients in the soil profile. GOSSYM requires constants and rate coefficients that were obtained under closely controlled and monitored environmental conditions, called the Soil Plant Atmosphere Research (SPAR) units. In an early BSF award (1978), D. Baker and A. Marani investigated the effects of water stress on vegetative growth and on carbon exchange rate (CER) in cotton canopies in the SPAR units.

The collaborative research between D. Baker and A. Marani during BARD award IS–181-80 delved deeper into the effects of drought stress (DS) and its effect on leaf senescence and the recovery of the leaf canopy from stress following re-watering. Equations were developed to express the effect of DS on the photosynthetic rate and its effect on the growth rate of vegetative biomass and plant height. The controlled SPAR experiments were complemented by field validation in Israel of the improved model. As a result of this study GOSSYM was expanded to include irrigation. Yield of irrigated cotton is usually two to four times greater than dryland cotton, depending on the absolute amount of irrigation and the type of irrigation system.

The GOSSYM model was later coupled to an artificial intelligence expert system, COMAX to enhance the decision-making capabilities of the simulator.

3 Academic Impact

3.1 Publications

1 peer-reviewed journal publication was published based on research from the single BARD award.

3.2 Capacity Building

Two graduate students were involved in the BARD supported research. Currently, 1 is in the USDA, ARS – Beltsville and 1 works in the Agricultural extension services in Israel.

3.3 Stakeholder's Collaboration

At the time of the model development, the fitting of multivariate data sets to describe individual physiological process rates was innovative. The methodology subsequently has become the most common mathematical method in crop simulation modeling. In Israel, extension officers and farm managers and in the US, the cotton industry and the USDA, ARS were involved in the validation and diffusion of the model as well as providing support.

Specifically, to Israel, no crop simulation had been applied to field crops prior to this work of A. Marani. Following this research, although the GOSSYM model was not implemented in full in Israel (see section 5), the Israeli cotton growers transferred to dynamic monitoring of crop-processes in order to apply the principles derived from the work of A. Marani.

The USDA Extension funded a technology transfer team to assist farmers with application of the model (later proven to be disruptive as it limited the crucial connection between the farmers and the model developers).

In the mid-90's, A. Marani developed the Cotton-2K[1] model which was derived from GOSSYM-COMAX. Its main purpose was to make the model more useful for conditions of cotton production under irrigation in the arid regions of the Western USA. The main effect of these changes was to improve the accuracy in the calculation of evapo-transpiration, which also affected related variables and to include a routine for sub-surface drip irrigation. The weather-related procedures have been tested and calibrated for the following regions: California San Joaquin Valley, Arizona (Phoenix - Tucson area), Israel Coastal Plain, and Israel Upper Galil (Hula valley area).

The Cotton-2K model has been directly and indirectly used and tested by many researchers. Recently (2014), the Cotton-2K model has been merged with the Precision Agricultural-Landscape Modeling System (PALMS)[2] by R.J. Lascano from Texas Tech University to

[1] https://sites.google.com/site/maranicotton2k/

[2] Molling et. al., *Journal of the American Water Resources Association*, Vol. 41, No. 6, 2005, pp. 1289-1313, doi:10.1111/j.1752-1688.2005.tb03801.x

develop the new model PALMScot[3] that evaluates water balance and harvest of cropping systems at the landscape-scale, e.g., ¼-section of land. Accordingly, it requires extensive input data to execute the model and this is perhaps the largest hinderance that prevents the widespread use of models in producer-oriented applications. For use as a commercial tool, the developer envisions a centralized server and interactive applications that allow the cotton grower to provide the required input data to run the model and a menu of output options to manage the crop. This could provide a wide range of management scenarios subject to economic analysis and risk assessment. Currently, ARS does not have the resources to implement such a program[4].

4 Commercial Engagement

From the mid-80's, the US National Cotton Council was instrumental in obtaining increased soft and hard money for expanded efforts to get GOSSYM on farms across the Cotton Belt (South-East United States) as a decision support system.

5 Practical Agricultural Applications

The GOSSYM/COMAX system began pilot testing on US commercial farms and experiment station plots in 1984. The number of commercial farms using GOSSYM-COMAX increased gradually until it peaked in 1991 and 1992 with around 100 direct users and another approximately 250 users that were facilitated by consultants[5]. Farms were located in in all fourteen cotton growing states across the Cotton Belt in the United States. The majority of the producers used the GOSSYM model as a decision support system for determining the application of plant growth regulators, crop termination, nitrogen utilization and irrigation practices in efforts to maximize profit, minimize risk and optimize input[6].

Use of the model required labor intensive "plant mapping" which was done by the farmer only a few times during the growing season. At the end of the season, based on the farmers input files, plant maps and yield data, the ARS team validated the model and modified some of the rate equations to improve agreement between field observations and model output. After several years, the developers realized that continuing improvements in the model were no longer giving the desired improvements in the simulations. Simulating

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[3] J.D. Booker, 2013, Ph.D. dissertation, Texas Tech, Modeling Landscape-Scale Water Balance in Irrigated Cotton Systems.

[4] Personal Communication, R. Lascano, USDA-ARS, Lubbock

[5] (a) Baker et al., GOSSYM: The Story Behind the Model, 2015, https://www.researchgate.net/publication/253950867_GOSSYM_The_Story_Behind_the_Model (b) J. M. McKinion et al., *Agricultural Systems* 31 (1989) 55-65

[6] (a) Ladewig, H., E. Taylor-Powell (1989) An assessment of GOSSYM-COMAX as a decision support system in the U.S. Cotton Industry. College Station, TX: Texas Agricultural Extension Service, 51pps. (b) Ladewig, H. and J.K. Thomas (1992) A follow-up evaluation of the GOSSYM-COMAX COTTON program. College Station, TX: Texas Agricultural Extension Service, 51pps.

crops from previous years with the newer model often gave inconsistent results. However, the results were good enough that most farmers continued year after year and new farmers joined the effort.

A number of reasons led to the demise, in the early 1990's, of the GOSSYM-COMAX use on commercial cotton crops, many of which were periphery to the utility and benefit of the model. These included the advent of new coding languages, structural changes in the USDA-ARS units that had led the development and extension services for the models use, the granting of the code rights to a private entity that proved unsuccessful in its continued work with the farmers and the cost of necessary plant mapping.

D. Baker became increasingly aware of approaching a chasm in the farm operations. He retired from the USDA laboratory at the end of 1989 in hopes of exploring the chasm and in finding a way to build a bridge. He continued to work for 15 years as an Agricultural Consultant on several very large cotton plantations in the Mississippi Delta[7]. In these years, GOSSYM was adapted into a true crop management decision support system (renamed GOSSYM CONSULTANT) in which the farmers and consultants worked closely together to make weekly adjustments to the cotton production program.

On the one hand, a more intensive effort at the farm level was needed, both spatially and temporally. However, to accommodate this, a plant mapping approach was developed that was greatly simplified but highly effective. The area was flagged in several locations and. plant map data collected at each flag weekly. Up to first bloom; plant counts, plant height and mainstem node numbers needed to be recorded. After first bloom, only numbers of green, open and rotted bolls were needed._ The field procedure took six minutes or less at each flag, and the consultancy technicians were mapping up to 2000 acres a day. The result of this development work and the "on-site" interaction between the model developers and the farmers led to a truly practical and accurate GOSSYM based cotton crop management decision support system leading to yield improvements and cost-effectiveness decisions. The bridge between the research laboratory where the process level model provides a matrix for the application of new research knowledge and farm practice was completed and tested. The Marani research on the physiological effects of drought on each of the plant processes is a good example of that.

The GOSSYM model is still the most widely used cotton growth model and is applied extensively by research programs for testing hypotheses and for providing policy makers with economic and policy decisions. Cotton-2K is today the most preferred cotton model for arid regions that lack ample amounts of water such as Arizona and Texas. The research group at Mississippi State University, previously led by D. Baker, continued to update and improve the GOSSYM model throughout the '90s under the leadership of K. Reddy as new

[7] Baker Crop Consulting LLC.

information became available. The modifications have increased the model's sensitivities to a wide range of environmental conditions including future climatic conditions.

Since 2000, the literature has demonstrated a marked increase in journal articles that describe applications of the cotton models previously developed, and fewer articles focus on development of new models[8]. The cotton simulation models are being used to assess decline in yields (since reversed), effects of climate changes (e.g. shifts in in CO_2, temperature, water vapor and radiation), for tillage and erosion studies, to test the potential effect of fertilizer replacements, for breeding predictions, changes in drainage patterns and for assessing precision agriculture and integration of sensor data with models.

Within Israel, the GOSSYM model was not fully adopted in the field due to its complexity. However, the work of Marani led to a profound change for the Israeli growers who started to monitor and document prominent parameters included in the irrigation module developed by A. Marani. Initially dry leaf matter and later plant height. These parameters together contribute to the indices and coefficients used to calculate the irrigation schedule, rates and method as a function of measured evaporation. This coefficient methodology is used till today for the total cotton crop grown area in Israel.

In addition, A. Marani promoted the use of pressure chamber measurements of leaf water potential along the growing season, for which he derived the linkage to the daily photosynthetic rate, which is used in assessments of any determined irrigation regime.

In the US, despite discontinued use of the model as an applied framework, Kater D. Hake, the current VP at Cotton Incorporated, provided input that the concept behind GOSSYM of dynamically monitoring the whole plant physiological processes has an impact on US cotton growers till today. The model concepts were effectively disseminated and diffused amongst the cotton extension services agronomists and managers of cotton fields *via* presentations, discussions and day-length seminars, thus trickling down and across to farmers and, over the long-term, proved to be very effective in providing an extensive group of cotton growers with an understanding of the ongoing requirements of their crop and having an impact on US cotton yields till today[9].

Outside of Israel and the US, the GOSSYM model has been used in Spain, Greece, China, The Philippines, Australia (modified), Cameroon, and Thailand.

[8] Thorp et al., The *Journal of Cotton Science 18:10–47 (2014)*
[9] Personal communication with current VP at Cotton Incorporated

6 Economic Impact

6.1 Investment Cost

BARD contributed $180,000 in research funds between 1981 - 1984. Another award of about $180,000 was awarded by BSF in 1978, before the foundation of BARD. We relate to these two awards as a BARD investment.

6.2 The Benefits

The economic benefits from the use of GOSSYM stem from changes in use of nitrogen, water, insecticides, growth promoters and increased harvest yields[10]. A number of publications report an average benefit of $112 - $169/ha for US users, with a broader range of average annual benefit of $90 - $350/ha when differentiating between new and experienced users[11]. For our calculations we use an annual benefit of $140/ha.

The average area of cotton crops on the US farms that used GOSSYM/COMAX in the 80's was 730 hectares[11c]. At the peak of its use in 1991/1992 there were ~350[12] users, such that we estimate a total area of its application as 254,000 hectares. Following cessation of the model's distribution by the USDA ARS around 1993, the model was applied, in an improved mode, by D. Baker as a private consultant on an average of ~ 3300 ha annually until 2008. Details of the area to which the model was annually applied are in Appendix B.

Within Israel, the parameters outlined in the GOSSYM model led to a profound change for Israeli growers. They started to monitor and document prominent parameters included in the irrigation module to contribute to the indices and coefficients used to optimize agro-technic protocols. This coefficient methodology is used all over the Israeli cotton industry today. An analysis of average cotton harvest yields 5 years prior to and 10 years following the implementation of these principles, shows an increase in yield of 220kg/ha. Israeli cotton growers, extension officers and involved parties were asked to evaluate the role of the GOSSYM parameters towards this increase in order to evaluate the BARD attribution. All were of the opinion that the BARD research outcomes contributed; some noted they do not have the tools to assess whilst others suggested a range of fractional contributions up to a maximum of 50%.

In the US, based on the perpetuation of the models concepts downstream amongst growers till today (see section 5) and its contribution to increased yields over time we estimate the

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[10] See Table 1 in McKinion et.al., Agricultural Systems 31 (1989) 55-65

[11] (a) J. M. McKinion et al., *Agricultural Systems* 31 (1989) 55-65 (b) Ladewig, H., E. Taylor-Powell (1989) An assessment of GOSSYM-COMAX as a decision support system in the U.S. Cotton Industry. College Station, TX: Texas Agricultural Extension Service, 51pps. (c) Ladewig, H. and J.K. Thomas (1992) A follow-up evaluation of the GOSSYM-COMAX COTTON program. College Station, TX: Texas Agricultural Extension Service, 51pps. (d) BARD 10-year evaluation report.

[12] 100 direct users and an additional ~250 farms where it was applied with the help of consultants. See section 5

yield increase per decade based on the average yield increase in 3 dominant cotton growing state, Mississippi, Texas and Virginia, which was ~ 150 kg/ha per decade (See Table 1).

We attribute 1% of the extra revenue for total US yields during the 80's to GOSSYM by matching the gain of the models contribution per year with the estimated gain based on the known area to which the model was applied and the known average economic benefits per hectare. The fraction of the extra revenue attributed to the model is increased by 1.5% per decade according to an assumption of slow assimilation that matches the gradual long-term impact on US cotton crops till today (see section 5).

This is a conservative estimate as the contribution of GOSSYM over time to the increase in US yield (of the fraction not attributed to genetics) was probably much greater[13]. In Israel, the parameters of the model were immediately assimilated all over the cotton industry and therefore, we attribute 30% of the Israeli yield increases to the model. Table 1 shows the economic benefit assumptions and calculations. In line with the methodological rule of this evaluation project, we terminated the calculation in 2013, 30 years after the model was first implemented.

Table 1: The Economic Benefit Assumptions and Calculations

	Acala Cotton	**Improvement**	**Farm Gate Price**	**Revenue of Extra Yield**	**Extra Revenue Attributed to the Model**	**Extra Revenue Attributed to the Model**	**Average Annual Cotton Area**	**The Model's Contribution per Year**
Years	**Average Yield kg/Ha**	**kg/Ha**	**$/kg**	**$/Ha**	**%**	**$/Ha**	**Ha**	**$M**
Israel								
1972-1981	1,317							
1982-1991	1,587	270	1.32	356	30.0%	106.9	45,020	4.81
1992-2001	1,760	443	1.28	567		106.9	20,120	2.15
2002-2013	1,963	646	1.28	827		106.9	10,634	1.14
The US								
1972-1981	472							
1982-1991	625	153	1.32	202	1.0%	2.0	4,304,640	8.70
1992-2001	718	246	1.28	315	2.5%	7.9	4,661,200	36.72
2002-2013	877	405	1.28	518	4.0%	20.7	4,000,000	82.88
US + Israel								

[13] Personal communication, K. Hake, Cotton Incorporated

1972-1981								
1982-1991								13.52
1992-2001								38.88
2002-2013								84.01

6.3 Economic Results:

BARD including the BSF contribution invested as part of a chain of investments, that created the GOSSYM model. The work on water stress responses by A. Marani that was included in the module simulating soil water and root movement was of crucial importance to the success of the system. In particular, Marani's characterization of the only partial recovery of leaf photosynthetic ability on rewatering is extremely important. An evaluation of this research study in 1988 attributed 25% of the benefits of the early GOSSYM model to BARD. In current discussions with D. Baker this figure was accepted by him as a reflection of Marani's advances to the full model and we maintain this figure in the current evaluation.

- Net present value of the BARD's investment is $813 million, thereof $813 million already attained
- The Internal rate of return is 98%
- Benefit cost ratio is 288

Benefits that were not attributed to the project in this calculation:

- The contribution to other countries was not calculated due to lack of data
- The environmental impacts of better water management, controlled fertilizer application and changes in insecticide use were not included in the economic calculations.

Table 2: Main Results, 2018 Million Dollar-Terms

	The Project	BARD	BARD Attained	Thereof to the US	Thereof to Israel	Other Countries
BARD's Share in the Cost						
Dependence on BARD's Grant						
Share in the Benefit		25%				
Cost	2.8	2.8	2.8	1.4	1.4	
Benefit	3,263	816	816			
Net Present Value	3,260	813	813	766	47	0
Internal Rate of Return	158%	98%	98%	124%	39%	
Benefit Cost Ratio	1,153	288	288	541	33	

6.4 Sensitivity Analysis

The low and high alternative assumptions used in the sensitivity analysis were brought together to estimate results under pessimistic and optimistic scenarios. Table 3 displays the net present value sensitivity results, between the low result: $223 million, to the high result: $1.6 billion.

Table 3: NPV - Sensitivity Analysis, 2018 Million Dollar-Terms

			BARD's Share in the Benefit		
			Low	Central	High
			15%	25%	35%
Change in Benefit	Low	50%	242	405	568
	Central	100%	487	813	1,139
	High	150%	731	1,221	1,710

7 Appendix A: BARD Awards

Table 3: Details of the BARD award

Project No	Full Title				
	Investigators	Institutes	Budget	Duration	Start Year
IS–181-80	Development of a Management-Oriented Dynamic Simulation Model for Cotton Production				
	A. Marani D. Baker	Hebrew University USDA	$180,000	3 year	1980

8 Appendix B: User area of the GOSSYM-COMAX model in the US and Israel

Table 4: The farmed user area of the GOSSYM-COMAX model in the US and GOSSYM coefficients in Israel

	US Ha	Israel Ha
1984	1,460	63,300
1985	7,300	65,400
1986	21,900	46,500
1987	51,100	40,000
1988	94,900	48,000
1989	131,779	30,300
1990	182,989	31,000

1991	254,100	13,000
1992	254,100	17,500
1993	79,924	15,400
1994	25,139	20,200
1995	7,907	23,500
1996	2,067	28,200
1997	1,919	28,700
1998	6,873	28,800
1999	2,016	15,100
2000	2,016	9,600
2001	2,130	14,200
2002	7,622	11,500
2003	5,700	9,800
2004	4,626	13,900
2005	4,800	10,200
2006	4,800	12,800
2007	3,160	11,040
2008		5,200
2009		3,910
2010		3,960

9 Appendix C: Information providers: Personal communication

Don Baker - PI of BARD grant, Baker Crop Consulting LLC, formerly USDA, ARS Mississippi

Avishalom Marani – PI of BARD grant, Plant Sciences and Genetics, Hebrew University

Kater D. Hake – VP Agricultural & Environmental Research, Cotton Incorporated

Yehoshua Saranga – Plant Sciences and Genetics, Hebrew University

Arie Bosak – Extension Office, Field and Vegetable Crops, Israel Ministry of Agriculture

Jhonathan Ephrath - Institute for Agriculture and Biotechnology of Drylands, Ben Gurion University

Jonathan Spenser – CEO, TerraVerde Agriculture Ltd.

Robert Lascano – USDA, ARS, Wind Erosion & Water Conservation , Lubbock, Texas