Agronomic concepts and approaches for sustainable cotton production

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ABSTRACT

Stagnating yields, lower cotton prices, higher input costs and concerns about environmental protection, coupled with the World Trade Organization agreement, have imposed the need to produce more sustainable and competitive cotton crops. Additionally, the cotton crop has emerged as one of the major consumers of agrochemicals for yield maximization and because the crop requires a comparatively longer growing season compared to other row crops. Furthermore, cotton is a perennial plant grown as an annual and is reputed to have the most complex growth habit of all major row crops. This greatly complicates the production of cotton for efficient management and profitability, sustainability and protection of the environment. This paper presents an overview of agronomic concepts for consideration in current or alternative systems for lowering inputs, sustaining production, protecting the environment, and maintaining or improving profitability. The major concepts covered include: ***Crop rotation:*** *Monoculture of "competitive" crops has commonly replaced crop rotation, because of the false view that crop productivity is calculated on an annual basis instead of over an extended period. Appropriate crop rotation systems are of high priority for integrated management of soil fertility, plant pests, diseases and weeds, and for increases in yield and quality.* ***Soil compaction:*** *Intensive and incorrect use of machinery has led to rooting problems, poor growth and lowered yields. Conservation tillage, including minimum and no-till practices, should reduce wind and water erosion, as well as lower the costs of fuel, labor and other inputs.* ***Judicious fertilization:*** *Research has shown that systems with reduced fertilization are feasible for high yields. Emphasis should be on the correct timing and availability of nutrients. Foliar fertilization, for main nutrients, should only be used to correct a deficiency on a timely basis.* ***Irrigation:*** *The availability of water is one of the most critical factors for optimum cotton yields. Attention should be paid to water conservation, through correct land preparation, optimum planting times, and efficient use of irrigation water in order to decrease water consumption and conserve this precious resource.* ***Early sowing:*** *The earliest possible sowing is of major importance, especially in marginal cotton countries, because it maximizes season length, helps plants better exploit the earliest favorable period for plant growth, and leads to avoidance of late-season insect and weather problems. Sowing on beds or covering the row with plastic film during emergence can enhance the effectiveness of early sowing.* ***Narrow row spacing:*** *Conventional row spacing of 1 m between rows was imposed by machinery requirements, mainly mechanical pickers. However, numerous studies show that narrow row systems are superior to conventional systems because they provide more desirable plant distribution for improved exploitation of resources, and early canopy closure for efficient radiation use. Low input growing systems are expected to reduce plant growth and consequently increase the effectiveness of closer rows. The advent of genetically engineered herbicide resistant cottons has facilitated weed control in closer rows.* ***Plant growth regulators (PGRs):*** *PGRs and nutritional additives should only be used when needed. Research has demonstrated that most PGRs are not effective in significant yield enhancement. In most cases, appropriate good farming practices should successfully control and balance growth and yield development.* ***Crop monitoring:*** *Recent improvements and simplification of crop monitoring techniques have greatly aided in the achievement of optimum crop management, particularly in the detection of crop stress for timely amelioration, and also for late season decisions.* ***Organic cotton:*** *Production of organic cotton constitutes a novel production system requiring premium prices, abundant hand labor, and locations free of harmful pests. In regard to sustainable production, production costs may increase and competitiveness decrease.* ***Varieties resistant to stress:*** *Traditionally, plant breeders have strived to create high yielding varieties, which are generally responsive to high inputs. However, research is now aimed at the evaluation of a wider range of germplasm for the creation of low inputs demanding varieties with more tolerance to biotic and abiotic stresses.* ***Transgenic varieties:*** *The very rapid expansion of transgenic cotton varieties verifies their successful contribution to the control of weeds and some key insects. However, there are cases where yields and agronomic performance of transgenic varieties have not been as consistent as hoped. Transgenic varieties have great potential, but should only be adopted when economic returns warrant their use.* ***Integrated pest control:*** *The principles of integrating pest control within the whole production management system should be evoked in both low input*

and intensive cotton systems for efficient, profitable and sustainable cotton production.

Introduction

Since 1930, there has been a profound increase in crop yields and animal production due to supporting research and agricultural policies. However, the intensification of agriculture aimed at yield maximization has resulted in the overuse of chemical fertilization, irrigation water, agrochemicals and soil mechanical tillage, as well as the abandonment of rotation, and genetic erosion. The intensive agriculture with high inputs, and with the substantial subsidies, in developed countries, given to the production, and not for improved quality has led to: production surpluses, high cost of production, pollution of the environment, deterioration of the quality and over competition against third world countries (Galanopoulou-Sendouca *et al.,* 2001).

The 1992 World Summit in Rio de Janeiro assembled to deliberate on how to heal the ailing environment. Ten years later, last September, world leaders convened at the World Summit on Sustainable Development in Johannesburg (in the same country which hosts the 3rd World Cotton Conference) to reassess the planet's condition and decide about future policies.

Sustainable agriculture is among the most important components of sustainable development. Since the early 1990s, the World Trade Organization (WTO) agreement, coupled with environmental initiatives, has imposed the need for reform in crop farming aimed at producing internationally competitive crops, while dealing with ecological disturbances caused by agricultural activities. However, the path to sustainable agriculture is a matter that needs careful consideration for it is possible, under the mask of environmental protection, to deteriorate the farming system and crop productivity in a way which may exaggerate farm problems and human starvation (Galanopoulou-Sendouca, 1998). As it was pointed out in Johannesburg, the issue is not environment versus development or ecology versus economy. Sustainability and development must be integrated, as both bioengineering and organic farming can play their own unique and important roles (Kluger and Dorfman, 2002).

In cotton, economic components for crop profitability restrain optimism. Cotton yield appears to be on a plateau or short decline since 1987 (Meredith, 1998). Since 1997/98, the indicator of international prices has been lower than the long-term average. The Cotlook A index for 2001/02 is the lowest in the last 29 years. Low prices will affect cotton yields in many countries, lowering the average world cotton yield (ICAC Recorder, 2002a). Furthermore, recent world consumption forecasts have been lowered due to economic weakness of developing countries.

Stagnating yields, lower cotton prices, higher input costs and concerns about environmental protection, coupled with the World Trade Organization agreement, have imposed the need to produce more sustainable and competitive cotton crops. For example, the cost of controlling insects is one of the major production costs. It thus makes economic and environmental sense, to reduce the crop's dependence on farm chemicals. Additionally, the cotton crop has emerged as one of the major consumers of agrochemicals for yield maximization. The crop also requires a comparatively longer growing season compared to other row crops. Furthermore, cotton is a perennial plant grown as an annual and is reputed to have the most complex growth habit of all major row crops (Oosterhuis and Jernstedt, 1999). This greatly complicates the production of cotton for efficient management and profitability, sustainability, and protection of the environment. However, there is space for increased production inputs in some developing countries. Many developing countries use less inputs than are optimum because farmers face financial difficulties to buy inputs, e.g. Nigeria and Benin (ICAC Recorder, 2001). Singh *et al.* (2000) estimate that in India (Punjab region) there is still space to increase energy input in order to raise cotton crop, mainly for soil cultivation, irrigation and weed control (0,3% increase may lead to 2,5% increase of production).

Developing countries should take stock of what technology is already available (i.e. use of herbicides, acid delinted seed, and precision sowing, and the use of high plant populations), validate the appropriate technologies for their conditions and thereby raise the overall standard of their cotton growers.

More efficient production practices are a key to lowering production costs and improving cotton profitability. This paper presents an overview of agronomic concepts for consideration in current or alternative systems for lowering inputs, sustaining production, protecting the environment, and maintaining or improving profitability.

Crop rotation

Continuous cultivation of the same crop, leads to deterioration of the soil and makes it poor due to depletion of crop specific needs of natural resources, especially soil nutrients. However, within the framework of intensive agriculture, crop rotation has been replaced in most cases by monoculture of 'competitive' subsidized crops. There is also the false view that crop profitability is calculated on an annual basis instead of over a period of years.

The yield decrease in monoculture systems is attributed to "soil sickness". Crop growth and development is prohibited as plant resistance to diseases and insects is decreased. "Soil sickness" is also connected with the fact that different crops have different nutrient demands. Another dimension of "soil sickness" is the root excretions of toxic substances from certain plants with allelopathic adverse effect on the growth of other plants. Allelopathy has greater effects on weeds control (Lampkin, 1992). The most important advantages of crop rotation are:

a) Conservation or even improvement of soil fertility.
b) Control of plant pests, diseases and weeds due to great differences among crops. Many pests and diseases infest only certain crops, so that crop rotation is a main factor of Integrated Pest Management (IPM) (e.g. most cotton pests and weeds would be killed by rice flooding). Crop rotation is more effective in disease control than for insect control. For example, severe soil infestation by the fungus *Verticillium dahliae* Kleb, often causes severe cotton yield losses, and obligates farmers to grow an alternative crop for a few years.
c) Yield and quality increase of crops. Adding legumes, e.g. as green manure or forage in different cropping systems, can fully open up the limited land resources, increase the potential of soil and improve soil fertility. In China, legumes used as green manure incorporated into the soil 22,5 t/ha biomass, and decreased N fertilization for following cotton crop by 50%. Also, broad bean (*Vicia faba* L.) or peas (*Pisum sativum* L.) are inter-planted with wheat in the autumn or early winter and picked as fresh pods for vegetables. The residues are incorporated as basal manure for the succeeding cotton crop the next spring. Experiments showed that inter-planting broad bean gained 5.4 t fresh pods/ha, a bonus yield, and 16.8 t fresh matter/ha, which provided additional organic matter and nutrients (Chen, 1992).

In Greece, cotton cultivation has become, due to highly subsidized prices, a monoculture in some regions, e.g. Thessaly, and this situation has led to "soil sickness". Today, legumes and cover crops must be included in rotation systems to minimize inputs in cotton cultivation. Traditionally, cotton is rotated in Greece with winter wheat. Such a rotation permits the use of cover crops for green manure (Galanopoulou-Sendouca, 1998). On the contrary, the effect of sugar beet in cotton cultivation in Greece is considered negative based on various field observations and the personal experience of farmers. According to research data, increased soil compaction observed in plots planted to sugar beet combined with delayed cotton growth, support the hypothesis that the swollen sugar beet roots increase soil compaction, prohibiting root penetration of the following cotton crop (Galanopoulou *et al.,* 1998).

Long-term research is needed to identify the appropriate rotation systems for each region. In Pakistan, a cotton–wheat rotation gave the highest five-year average returns compared to systems such as cotton-sunflower, and cotton-maize (Ahmad *et al*., 1998). Double cropped wheat-cotton rotations in irrigated cotton systems in Australia provide high ground cover levels and significantly reduce soil erosion with a similar decrease in the off-farm movement of pesticides (Rohde *et al.,* 1998). Deep-rooted crops as safflower (*Carthamus tinctorious* L.) used in cotton rotation systems can improve the overall water and N use efficiencies of cropping systems and help minimize nitrate leaching to ground water (Bassil *et al.,* 2002).

In conclusion, appropriate rotation is the most effective factor for lowering production inputs and for successful sustainable cotton crop. The adoption or even the mandatory inclusion of crop rotation, in countries, such as Greece with high subsidies for cotton production, will restrict the expansion of cotton cultivation and consequently will limit the decline in prices. Crop rotation is included in the "Codes of good farming" imposed by the EU for subsidized "friendly to the environment" agricultural enterprises (Reg. 1259/99).

Conservation tillage

The intensive use of heavy machinery in connection with cotton monoculture initiated problems of soil compaction, which led to adverse effects on plant rooting and consequently crop yield. Additionally, the importance of conserving soil moisture and reducing energy and labor-related costs, as well as equipment requirements, have been a key concern in economic survival for farmers and that has led many of them to adopt conservation tillage practices (Barnet and Stevens, 1996; Larson *et al*., 2001). "Conservation tillage" was initially used for tillage practices that conserved soil by reducing the potential for wind/water erosion. However there has been an increasing realization that conservation tillage also greatly reduces the cost of fuel, labor and other inputs. Consequently there are a wide variety of approaches and terms under conservation tillage including reduced tillage, optimum tillage, minimum tillage, and no-till.

Soil erosion, especially in slopping areas with heavy rainfall and/or sandy land with strong blowing winds, is a severe problem for depletion of natural resources. According to Brown and Wolf (1984) 7% of the world surface cultivated soil is lost in a decade due to soil erosion, which appears, as a quiet crisis in the world economy. On a world scale, soil erosion is the main factor for soil fertility deterioration. Improved surface cover (or protection) from cover crops or minimal tillage facilitate water infiltration and prevent surface soil crusting, and thereby decrease soil erosion (James and Russel, 1996; Moseley *et al.,* 1996). The efficiency of different cover crops (vetch, rye, broad bean, etc.) as an independent practice or in combination with minimum tillage is well established provided there is no delayed destruction of the cover crop and the cost of the cover crop seed is not too high (Moseley *et al.,* 1996; Chen, 1992).

Concerning yields, it was found in Texas that in a burley-cotton rotation, cotton yield was always higher under no-till than under conventional system due to increased water conservation (Herman *et al.,* 1989; Weise *et al.,* 1994). Similarly, under irrigation in Greece it was found that cotton yield was higher under no-till compared to conventional systems due to better water and nutrients availability, apart from the benefits of reduced energy costs and less environmental pollution (Billalis *et al.,* 2000). Conservation tillage also proved profitable for cotton production in the high plains of Central Texas (Herman *et al.,* 1989). Also a method of establishing wheat after cotton by broadcasting the seed without any previous stalk chopping and/or tillage and seed incorporation by a light cultivator was studied under Greek conditions in comparison with conventional (ploughed) tillage. The results showed that wheat plant emergence and development were not significantly affected by the tillage treatment and yields from plots with unchopped stalks did not differ significantly from ploughed plots (Gemtos *et al.,* 1998).

In Sudan cotton yields from reduced tillage systems and conventional ones were not statistically different (Skeikl and Gadir, 2000). Reduced yields under no-tillage system were reported in Arkansas (Keisling *et al.,* 1993). Similarly in Alabama, yields from no-till treatments have not been competitive with conventional tillage on the silt-loam and silty-clay loam soils of the Tennessee valley (Reeves *et al.,* 1996). The success of minimum tillage appears to depend on the use of appropriate machinery for soil preparation and seed sowing, as well as weed control and crop rotation. Effective weed control is a critical factor for the success of reduced tillage systems. Genetically engineered cotton resistant to certain herbicides greatly facilitates the problem of weed control in narrow rows and no-till growing systems.

Judicious fertilization and irrigation

Fertilization

The effectiveness of chemical fertilization in combination with irrigation has led to the overuse of fertilizers, especially nitrogen, even though cotton is generally considered as a low fertilizer demanding plant. In Thessaly, the main cotton belt of Greece, there is surface and underground water nitrate pollution, due to excessive nitrogen fertilization (up to 240 N/ha) in cotton cultivation. The problem of water pollution with nitrates is intensified by excessive irrigation, which not only has adverse effects on crop productivity, but also leads to dangerous shortages of precious water reserves. Agricultural policymakers in many developed countries are close to imposing fees on farmers who exceed the economic and environmental optimum irrigation and fertilization level (Galanopoulou-Sendouca, 1998). Judicious timing of fertilizer application, and appropriate irrigation practices are included in the "Codes of Good Farming" which is compulsory for subsidized environmental projects in the EU. Research has shown that systems with reduced fertilization are feasible for optimum yields. Results from Greece provide strong evidence that conventional high levels of major production inputs, such as nitrogen fertilizer or irrigation water, did not result in yield increases compared to lower levels. Furthermore, low input treatments, generally led to an increased yield in the first pick, which represents the most important part of the total cotton yield and the highest fiber quality (Galanopoulou-Sendouca, 1998). Optimum yield response to N application varies among regions, varieties, irrigation levels and other cultural techniques and consequently is an ongoing concern of cotton producers. In Thessaly, Greece, yield seems to maximize near 120 N/ha, instead of 240N/ha used a few years ago (Galanopoulou-Sendouca, 1998). In Arkansas, yield response of all tested cultivars maximized near 112 N/ha (McConnell *et al.,* 2001a). A sound basic soil fertility program combined with plant tissue analyses should provide a means to limit excess fertilizer inputs while obtaining maximum economic yield.

The timing of nitrogen fertilizer application has changed in the last few decades. Instead of pre-plant fertilization nitrogen is applied now closer to the time the crop needs the nutrient (Gerik *et al*., 1998; Plunkett *et al.,* 2001). The correct timing and availability of nutrients may greatly enhance the effectiveness of fertilization and reduce environmental pollution. In countries, such as Israel and Greece, where drip irrigation is a common practice for cotton, fertigation is a promising technique according to research findings. Experimental results in Greece provide evidence that irrigation and fertilization in cotton in the form of fertigation may be reduced in accordance to the imposed low input agriculture without a serious variation in the cost/benefit ratio (Polychronides *et al.,* 1998). Correct timing may be also on cotton monitoring (see below).

Foliar fertilization for main nutrients (e.g. KNO_3) may be considered as an extravagant luxury for cost production efficiency. Cost increase is higher when several foliar sprayings are suggested to meet for nutritional requirements especially in cases there is no need for pesticides application. Foliar fertilization, for main nutrients, should only be used to correct an urgent deficiency on a timely basis.

Precision agriculture is a new approach to integrated crop management, which encompasses fertilization of cotton. Producers that have adopted precision agriculture maintain that it holds great potential for benefits to the environment and for economic gains. However, farmers need to realize how to use the complicated new technology to improve profit. Furthermore, the use of precision agriculture is not appropriate for small-size farms and/or in developing countries where the necessary technology does not exist (Robinson, 2002).

Irrigation

Only 2.5% of world's water is fresh water of which only a fraction is accessible, and agriculture accounts for about two-thirds of the fresh water consumed. Therefore, protection of this precious natural resource, which becomes increasingly limited in supply, must be conserved through careful agricultural management. Within the concept of "more crop per drop", this calls for more efficient irrigation techniques, planting of drought - and salt - tolerant crop varieties that require less water, must be implemented for sustainable use of water.

The cotton plant originates from arid areas and exhibits more drought tolerance than other row crops, such as maize and soybean (Oosterhuis and Wullschleger, 1988). However, this characteristic is limited in most current commercial varieties (Meek *et al*., 2002) and cotton does not grow well without adequate water (Oosterhuis and Bourland, 2001). Consequently, the availability of water is one of the most critical factors for optimum cotton yields. As water availability is becoming a limiting factor for successful cotton growing, attention should be paid to water conservation, through correct land preparation, optimum planting times, and efficient use of irrigation water in order to decrease water consumption and conserve this precious resource.

One effective irrigation system is drip irrigation. Drip irrigation has expanding rapidly in Greece, especially in Thessaly where it covers approximately 50% of the cotton acreage. It is mainly used in regions with intense water shortage problems and lack of irrigation delivery networks but with high crop yielding capacity, so that covering the expenses of buying the system can be achieved during its relatively short life span. Usually, a single dripper line supplies water to two adjacent rows. Drip irrigation is broadly used in Israel, where the shortage of water is very serious and where the drip irrigation system had its origin. Compared with sprinkler irrigation, yields of crops irrigated by drip irrigation are generally 15-20% higher, according to research work carried out for at least 15 years (Goren, 1994). The main advantages of drip irrigation are: effective use of water (approximately 40% less water in comparison to surface systems as there is not much waste due to evaporation or its movement below the root system), and the more efficient and cheaper fertilization and weed control applied through the system (Goren, 1994). In South Africa cotton yield under drip irrigation was 24-65% higher than sprinkler irrigated cotton (Dippenaar *et al.,* 1994). However, fertigation of cotton was slightly inferior to the conventional fertilization program but proved to be easy, accurate and labour saving.

Early sowing

The earliest possible sowing is of major importance, especially in marginal cotton areas, because it maximizes season length, helps plants better exploit the earliest favorable period for plant growth, makes maximum use of seasonal solar radiation, and leads to avoidance of late-season insect and weather problems. Early sowing is usually related to higher yields, especially in years with a reduced growing season (i.e. period with minimum temperature >15 °C), and/or decreased sunshine duration. The above holds true even in cases with reduced emergence and plant population (up to 50% of the optimum population, provided the gaps are uniform), as it is well known that the cotton plant with its indeterminate growth habit is capable of compensating for great losses in population densities (Chlichlias *et al.,* 1977; Galanopoulou-Sendouca *et al.,* 1980). The optimum date of sowing in Greece is usually 10-20 of April and the latest date is the end of April. Delayed sowing after that period, leads to drastic yield reduction, such that sowing in June has only a limited probability of producing any yield (Christidis, 1965). Nowadays, early sowing has generally been adopted by cotton farmers. In Greece for example, the optimum date of sowing has been moved approximately 10 days earlier than previous.

Generally, an earliness management program helps the cotton crop better utilize the specific growing season, escape late-season pests and allows a better chance of escaping adverse late-season weather (McCarthy, 1996). Furthermore, early harvest permits the incorporation of the cotton crop into successful rotation systems. However, there is an optimum earliness for each case and cotton crop should exploit the whole growing season for yield optimization (Galanopoulou-Sendouca *et al.,* 1980). As cotton plant is very sensitive to low temperatures, the success of early sowing is pursued through cold resistant varieties and cultural techniques, such as sowing on beds or covering the row with plastic film during emergence.

Cotton emergence under plastic film

The method of early cotton sowing under plastic film is broadly used in Spain to guarantee seed germination under early sowing (Portero, 1994). For Greece, especially in northern regions, which are characterized by short growing seasons, this system contributes to early and uniform plant emergence, an important component for the crop's success. The use of plastic film in the early stages of cotton cultivation is supported by research data from the 1970's (Galanopoulou-Sendouca *et al*., 1978) as well as evidence from farmers who have adopted the recently mechanized method. However, there are some contradictory results, and further investigation is needed. Row covering with polyethylene strips increased soil temperature by approximately 2 °C, which improved plant emergence by 9% and shortened the emergence duration from 18 to 11 days, with a 20% yield increase. The covering was more effective under adverse conditions of low temperature during early sowing and low soil moisture (Galanopoulou *et al.,* 1978). Recent research in Greece showed that higher yield overcompensates for the cost of plastic, and that earlier cotton maturation guarantees successful cotton harvesting (Stathakos and Galanopoulou-Sendouca, 1996). Colomer and his colleagues (1998) found that the productive potential of cotton sown under plastic mulch is greater than traditional sowing; however success ultimately depends on the growing practices used. Frequent irrigation with appropriate, timely fertilization is needed due to a shallow root system (Stathakos and Galanopoulou-Sendouca, 1996).

The continuous use of plastic films will create environmental problems which may be faced by the production and use of either biodegradable plastic or films from starch, e.g. cornstarch (Anonymous, 1991).

Cotton sowing on beds

The necessity of successful early sowing, especially in wet regions with heavy soil, where drainage is prohibited, led to the use of beds in the USA and later in other countries. Soil drainage is improved and consequently temperature increases resulting usually in accelerated and improved emergence as well as lower Verticillium wilt infestation. Furrows between beds facilitates mechanical picking and furrow irrigation (Galanopoulou-Sendouca *et al.,* 1978). The effectiveness of the method relies on appropriate machinery and effective herbicides applied during bed formation. Absence of weeds at sowing is a prerequisite for success, as weed control before sowing is problematic. Where genetically engineered herbicide resistant cotton varieties are used, the control of these weeds may be easily accomplished.

Narrow-row spacing

Conventional row spacing of 1 m between rows was imposed by machinery requirements, mainly mechanical pickers. However, numerous studies have shown that narrow-row systems can be superior to conventional systems because they provide more suitable plant distribution for improved exploitation of resources, and early canopy closure for efficient radiation use (Galanopoulou-Sendouca *et al.*, 1980).

Cotton producers in the United States and in other cotton producing countries have made continued attempts to grow the crop on various row spacing and row configurations, including double rows, on beds or on the flat soil, ranging from six to 14 inches and single rows ranging from 19 inches to 40 inches. Most narrow-row cotton currently consists of 30 inch. Increased yields is the most common rationale for using narrow-row cotton, but convenience of growing it with other crops which lend themselves to 30 or 32 inch rows (e.g. corn and soybean) is also important. Other benefits reported include water conservation, early maturity, better response to the growth regulator pix, improved lint quality, fewer pesticide applications, and better use of solar radiation (Galanopoulou *et al.,* 1980; Weir, 1996; Bartzialis *et al.,* 1998; Spencer, 1998). Increased plant population densities with narrow rows decrease also *Verticilium* wilt infestation and can compensate emergence losses (Lefkopoulou *et al.*, 1980; Galanopoulos and Galanopoulou-Sendouca, 1992).

The superiority of narrow-rows is more evident when the prevailing conditions prohibit full canopy closure in 1m rows. Such cases are expected to become more frequent with the use of low nutrients - demanding, short-season cotton varieties and the use of low input growing systems, which will reduce plant growth.

Since the 1980s in California, there has been an increasing trend in the use of transformed cotton pickers, which can successfully harvest cotton sown in 76 cm rows (Weir, 1996). Research data showed a yield increase in rows 76 cm apart compared to rows 102 cm apart. This superiority was associated with better plant exploitation of soil and solar energy is due to the spatial by uniform distribution of plants (Heitholt *et al.,* 1993). Early maturity was also documented and attributed to reduced plant growth and a lower first fruiting branch (Heitholt *et al.,* 1993; Robinson, 1991; Williford, 1992). This system is also currently being evaluated in Greece, with promising results (Bartzialis *et al.,* 1998).

Ultra narrow-row cotton (UNR) systems (i.e. with row spacing of seven to 30 inches apart) seem also advantageous in some regions, such as the High Plains in Texas, and in the Mississippi Delta but they can only be harvested with stripper harvesting machines, which are considered to deteriorate cotton fiber quality. The development of new cotton strippers with addition and improvement of field cleaners should increase farmer and research interest in UNR cotton. Also GE cotton (Roundup Ready cotton) can further contribute to successful weed control programs in a system that removes the possibility of cultivation and/or band application of herbicides. Potential benefits of UNR cotton production include reduced production costs, utilization of poorer soils, decreased soil erosion, utilization of the same equipment for cotton, soybeans and maize, and lower N requirements for maximum yield compared to conventionally spaced cotton (McConnel *et al.,* 2001). The advent of genetically engineered herbicide resistant cottons has facilitated weed control in closer rows, which was until recently severe limitation in UNR systems.

Plant growth regulators

Plant growth regulators are organic compounds, other than nutrients that affect physiological processes of plants when applied in small concentrations and provide numerous possibilities for altering crop growth and development. The possible benefits and uses of PGRs in cotton production include control of vegetative growth, increased boll retention, earlier crop maturity, preparation of the crop for harvest, and increased yields. These responses are a reflection of the interaction of genotype, cultural inputs and environment. Because of this complex interaction, crop response to PGRs is not always predictable and results, especially with yield enhancement, have often been disappointing, variable and inconsistent (Cothren *et al.,* 1996; Oosterhuis and Egilla, 1996; Oosterhuis *et al.,* 1998). Intensive cotton cultivation aimed at maximizing yield, often without cost considerations, led also to the foliar application of various nutritional additives such as amino acids or sucrose with questionable benefits and often with detrimental effect on cotton plant.

Previous review of literature concluded that plant growth regulator use in cotton is a viable option for effectively modifying plant growth and development. Success with growth retardants, yield enhancers and crop terminating compounds makes managing the crop an easier task. Suppressing excessive vegetative growth also allows for better control of insects and assists with harvest (Cothren, 1994).

PGRs are widely used in cotton. Among them, the most widely used is the growth retardant PIX (mepiquat chloride), which has been used as an important management tool for upland cotton, especially in the USA, for the past 30 years since it was registered in 1971. Results showed that when internode length increased (prior to applications of mepiquat chloride-Pix) at less than 5.5 cm/node, no response or even negative yield responses to Pix were obtained (Constable, 1994). When internode length was increasing at more than 6.5 cm/node, significant yield increases were obtained.

In a recent review, Oosterhuis and his colleagues (1998) stated that numerous field tests have been conducted across the U.S Cotton Belt comparing select PGRs for affect on yield, but most of the PGRs tested have failed to significantly or consistently increase yields. Even mepiquat chloride, the most broadly used PGR in the world, does not increase yield consistently.

Although Arkansas research has shown inconsistent yield responses of cotton to mepiquat chloride (PIX) applications, its use continues to be of interest to the state's producers. However, accumulated results from research with PGRs treatments did not indicate any significant yield, maturity, or growth advantages. Mepiquat chloride-based PGRs did not substantially alter cotton growth and development and the costs associated with PGRs negatively affected crop revenue (Benson *et al.,* 2001).

In conclusion, in low input growing systems PGRs should only be used when needed, until a better understanding of PGRs is fulfilled for more predictable crop responses and greater economic results. Until then, rational use is suggested with great attention on the appropriate dose and time of application in correlation to the developmental plant stage. Research has demonstrated that most PGRs are not effective in significant yield enhancement. In most cases, appropriate good farming practices should successfully control and balance growth and yield development.

Crop monitoring

As cotton plant is very responsive to changes in the environment and to management, it is essential that producers understand the development pattern of the crop and the stage-dependent requirements in order to avoid possible problems and protect yield (Oosterhuis and Jernstedt, 1999). Crop monitoring provides a precise means to follow crop growth and pinpoint problems for timely action (Danforth and O'Leary, 2001). Recent improvements and simplification of crop monitoring techniques have greatly aided in the achievement of optimum crop management, particularly in the detection of crop stress (e.g. poor or excessive plant growth) for timely amelioration, and also for late-season management decisions. Early detection of stress and timely crop management also improve economic inputs.

A model for cotton monitoring is COTMAN (COTton MANagement). The simulation model COTMAN derived from concepts of stress physiology research in Arkansas. COTMAN relies on recording the number of squaring nodes of the main stem and square retention before flowering initiation and after that on the number of sympodia above upper white flower (Nodes Above White Flower-NAWF). Plant monitoring provides opportunities for changing management to aid in fruit retention or modifying plant height (Plunkett *et al.,* 2001). It makes also use of the "good stress" manifested by slowing down of the terminal part when cotton plants approach physiological maturity so that resources are preferentially diverted to the developing bolls. Although the growth habit of the cotton plant is indeterminate, development eventually slows, with a substantially reduced rate of flowering and square retention. This stage is called "cutout" and signals the end of the useful flowering period. Too early cutout leads to earliness of maturation but also to reduced productivity, while late cutout results to the riskful lateness of yield maturation. Knowing when cotton crop is approaching cutout helps optimum crop management regarding end of insect control, end of irrigation and right time of defoliation. A reliable indication for cutout is NAWF. It was found that as NAWF decreases crop photosynthesis is also reduced (Bourland *et al.*, 1992, 1997). When NAWF=5, the crop has reached cutout and later flowers contribute little to the total yield or even act as parasites to the plant.

Research data support the concept of COTMAN but further validation is needed (Brown *et al.*, 2001; Kharboutli and Allen, 2001), for different regions with these unique prevailing environmental conditions and cultural techniques. Definition of the "Target Development Curve" should take into consideration the different conditions so that cotton development should exploit the whole growing season as it is defined by prevailing ecological conditions (temperatures, rainfall, solar radiation, soil properties).

Organic cotton

Organic cotton production, by totally excluding agrochemicals, has the least impact on the environment, i.e. it is the most "environmentally friendly" production system available. Organic products are produced for three years from the same fields and according to specific control before being appropriately certified and labeled, and finally sold for premium prices, as they satisfy the requirements of consumers who care about their health as well environmental protection. In Europe, organic production must obey all certification requirements set out in the EEC regulation 2092/91 on organic agriculture and food processing. This regulation is based on the International Federation of Organic Agriculture Movements (IFOAM) regulation (1995). Organized efforts to grow cotton without agrochemicals began in USA in 1989 (ICAC Recorder, 1993). Organic cotton is knitted into T-shirts, sweaters, infant wear, towels etc.

According to research data and practical evidence, maintaining yields in organic cotton production is not easy. The average yield decrease is estimated at 25%, especially during the first few years. Also, in most cases the cost of production is higher, mainly due to higher labor requirements, especially for weed control and expensive non-conventional means of insect control (Oosterhuis and Galanopoulou-Sendouca, 2001). In California (northern San Joaquin valley) a 15% decrease in yield coupled with an 11% higher cost per hectare resulted in 51% higher costs per kg of lint cotton, which can not be compensated by the estimated 44% higher lint price of organic cotton compared to conventional cotton (Swezey and Goldman, 1996). These results explain why in the USA, there was an initial expansion of organic cotton cultivation (~10,000 hectares) followed by a steady and sharp decline since 1995. This pattern also occurred in other countries such as Greece, probably due to the enthusiastic adoption of this new production system (i.e. organic cotton cultivation) before the solution of many problems concerning mainly pest and weed control (Marquardt, 2001). In 1999 the area in the USA partially recovered (about 6,700 ha, representing only about 0.1% of the total cotton area in the USA) but this is insufficient to meet their high industrial demands. Furthermore, the broad expansion of GE cottons in USA does not leave room for organic production. According to 1999 data, Turkey overtook the USA with 41% of the world organic cotton production, compared to USA 34%, Africa 13%, India 8% and Latin America 4%. However, as organic cotton is expected to eventually comprise more than 5% of total world cotton production, countries with low labor costs, abundance of hand labor and traditional, low input cotton cultivation (e.g. Turkmenistan), may benefit from organic cotton production. In Tropical West Africa research has provided evidence that, if market prices for organic produce could guarantee 20% price premium in the long term, organic cotton production might generate the same revenues as conventional cotton while reducing environmental pollution (Ton, 1998). It must be noticed that research on organic cotton in tropical regions as everywhere is still too limited to justify any judgment on its potential to be a viable alternative to conventional cotton.

Generally, the conversion of conventional cotton production to organically grown cotton is not as easy as other less intensive crops with fewer input requirements. Organic production demands higher levels of skill (especially for plant protection) than conventional production, but insufficient research has been conducted to provide guidelines for shifting from conventional to organic production. Rotation systems (obligatory in organic farming) must be evaluated to improve productivity, competitiveness and marketing of all organic products from the same enterprise. Priority in such rotation systems should be given to legumes which are easily incorporated into organic system, contribute to plant nutrition of the successive organic crops, produce excellent animal food, for biological animal production, which is in high demand. Mixed enterprises, of crop and animal production, may contribute to the success of organic farms. The success of organic production relies, mainly, on the use of fertile soils and of suitable varieties, and on the absence of pests, diseases and weeds. Similarly, other components of integrated pest management could contribute to the success of organic production. A comparative cost analysis of organic and conventional cotton production in Greece (Fotopoulos and Pantzios, 1998) concluded that unless specific solutions are developed that address the problems of biological control and make efficient combinations of production costs and yields possible, organic cotton growing will lag behind conventional system in economic performance. Alternatively, achievement of much higher price premiums than subsidies given through EU Reg. 2078/92 could also improve the economic performance of organic cotton.

Varieties resistant to stress

Within the framework of cotton growing intensification, cotton breeders (like all plant breeders) have strived to create high yielding varieties, which are generally responsive to high inputs. According to Constable

(2000), the high cotton yields in Australia, which are second only to those in Israel, is 45% attributable to breeding high yielding varieties, 25% from soil-nutrition-irrigation management, 20% from insect control, and 10% from disease management. Due to high yields, and despite relatively high costs for insect control, weed control, planting seed and ginning, Australia has one of the lowest costs of production per unit of lint. However, it seems that breeding work for yield increase has reached a plateau. In a study to determine if lack of progress in genetic improvement was partially responsible for stagnating cotton yields in the USA (Meredith, 1998) a comparison of obsolete versus modern cultivars indicated that breeding progress for yield peaked in 1987. According to these results Meredith suggested broadening the genetic base being used by breeders (Meredith, 1998).

The need to lower inputs, the confrontation of environmental problems, and the need of adoption of integrated crop management systems, has re-orientated breeding objectives. Use of appropriate varieties according to persisting insects, and biotic and abiotic stresses is of most importance. Research is now aimed at the evaluation of a wider range of germplasm for the creation of low inputs demanding varieties with more tolerance to biotic and abiotic stresses (El-Zik and Thaxton, 1998). For example, the creation of determinate varieties with fewer buds developed after 5 NAWF and naturally defoliating will improve sustainable growing systems.

More urgent is the increasing limitation of precious water sources, which greatly elevates importance of improved drought resistance. Although Oosterhuis (1989) showed that cotton was more drought tolerant than most other major row crops, there is a lack of significant drought tolerance in current commercial cultivars (Nepomuceno *et al*., 1998; Meek *et al*., 2002). Crosses between relatively diverse germplasm provided evidence that it is possible to select lines with improved physiological water use efficiency (Stiller and Constable, 1998). Moreover, promising information comes from Israel for cotton varieties tolerant to drought (Musaev, 1993). Resistance genes to dry conditions have been discovered in wild cotton species as *G. anomalum* and *G. thurberi* (Musaev, 1993; Nepomuceno *et al*., 1998).

Development of early-maturing cotton cultivars has become even more important than in the past to allow production in regions with short or dry seasons. Intensive concentration on this goal is of urgent importance for sustainable cotton. Future cotton germplasm should be screened for increased seedling vigor and rapid root system establishment to improve drought tolerance with the concept of the Multi-Adversity Resistance system used successfully in Texas (El-Zik and Thaxton, 1998). Heat tolerance should also be taken into consideration (Oosterhuis, 1997; Oosterhuis *et al*., 2003). Biotechnology is expected to play a major role to achieve these perspectives.

Transgenic varieties

Commercial production of transgenic cotton started in 1996/7, and in six years the area planted to GE cotton has increased to 6.8 million hectares, or 20% of the total area planted to cotton in 2001. However, the GE cotton area was only 13% of the total world area planted to GE crops during 2001. The major transgenic crop is soybean, accounting for 63% of total average. Corn is second with 19% of the total area (ICAC Recorder, 2002).

Cotton is grown in over 60 countries out of which only eight have approved the use of transgenic cotton. The countries that have allowed commercial production of transgenic cotton resistant to insects are Argentina, Australia, China, India, Indonesia, Mexico, South Africa and the USA. The herbicide resistant transgenic cotton, alone and in the stacked gene form, is allowed for commercial production only in Argentina, Australia and in the USA. Outside the USA, insect resistant Bt cotton is more popular than herbicide resistant varieties. In the USA in 2001/02, varieties having the herbicide resistant gene, alone and in conjunction with the Bt gene, were planted on over 97% of the transgenic cotton area, compared with less than 3% of area under Bt gene varieties (ICAC Recorder, 2002). GE crop varieties are not allowed to be cultivated in the EU territory, although it seems that EU legislation may change soon.

The transgenic cotton area is increasing. According to the USDA, GE cotton was planted on 78% of the total cotton area in the USA during 2001/02. Australia has put a limit on its transgenic cotton area in order to avoid the development for resistance; otherwise, the area planted to GE cotton would be much higher than 30% of the total. In South Africa, Bt varieties were planted on 40% of the total area in 2001/02. In China most of the cotton planted in 2001/02 was Bt cotton. India was seriously considering allowing commercial production of Bt cotton, and many other countries are evaluating the performance of transgenic Bt cotton (ICAC Recorder, 2001).

Large-scale application of modern biotechnology to cotton in seven countries by 2002 is an indicator of the technology success. Economic analysis of Bt cotton varieties versus conventional practices in Argentina indicates a two-thirds reduction in pesticide sprays (ICAC Recorder, 2001). The total cost of production per hectare was found to be high in Bt cotton over conventional practices, but net income per hectare and per kg was higher in Bt varieties. Transgenic Bt cotton in China also looks promising and has increased recently (ICAC Recorder, 2001).

Several reports from Australia, China, South Africa and other countries that have grown Bt cotton over significant areas indicate that the cost of production is lower with Bt cotton due to reduced spending on pest control (ICAC Recorder, 2002). Thus, pest pressure/ number of sprays per season to control target bollworms and the cost of pesticides versus the cost of the technology fee will determine the extent of savings in the cost of production. However, if the target bollworms do not become a major threat in a particular year, and a farmer has already paid the technology fee, savings in the cost of production could be negative (ICAC Recorder, 2002).

Transgenic cottons expressing insecticidal proteins with activity against one or more key pests offer great scope to allow the integression of a wide range of IPM compatible tactics and consequently to enhance IPM success (Fitt, 1998). The development and use of transgenic tolerance to herbicides is influencing positively some cropping systems, allowing changes in weed control strategies, row spacing and mechanical harvesting methods.

However, the initial euphoria for transgenic cotton is slowing down according to very recent results. Main concerns and criticism are as following:

- The Committee of the Australian Cotton Growers Research Association (2001-2002) makes it clear that Bt is in some circumstances failing to control the principal target pest it was introduced for, i.e. *Helicoverpa armigera*, which is the predominant race of bollworm in many countries, such as Greece. So, farmers in Australia are now being advised to spray additional insecticide on Monsanto's GM Bt cotton known as INGARD "under conditions of reduced INGARD plant efficacy". The same Committee also expressed concerns about the sustainability of the Bt technology due either to potential build up of resistant insects, or inadequate expression of the Bt gene in the plants, or both. Previous results in Australia clearly showed that the efficacy of Bt cotton plants in killing *H. armigera* larvae declines during the growing season (Daly and Fitt, 1998). Recently, Oosterhuis *et al.* (2003) have reported the use of a protein translocation enhances foliar spray to increase endotoxin levels and subsequent bollworm mortality.
- Chinese researchers also found that the use of Bt cotton, which is designed to target bollworms, was leading to larger populations of other cotton-eating pests, which could cause unpredictable disruptions to the environment (Associated Press, 2002).
- In India, the initial euphoria for the Bt cotton appears to be strangely missing, according to recent data. Bt cotton was found prone to leaf curl virus in North India (Revathy, 2002). Also yield of the Bt cotton crop was much more adversely affected by the drought than other cotton varieties, and economics were proved against Bt cotton, mainly due to the quadruple higher price of Bt cotton seeds in comparison to existing conventional cotton seeds (Shah and Banerji, 2002).
- Although greater benefits from Bt cotton was recorded in South Africa (ICAC Recorder, 2001), doubts are now being expressed in Africa concerning the gain from genetically modified crops (The Nation, Nairobi, June 3, 1999).
- Bt cotton is effective for control of tobacco budworm (*Heliothis virensis* F.) but the control of bollworm (*Helicoverpa zea* Boddie) and other lepidopterous pests has been less dependable (Lorenz *et al.*, 2001). Effectiveness also varies with the species of bollworms (ICAC Recorder, 2002). If a particular species of bollworms is vigorously controlled for a number of years, which the Bt cotton is meant to do effectively, some minor insects may become major insects. It is also feared that some insect species may emerge, which could be even more difficult to control with current insecticides. Similar apprehensions are also true of weeds (ICAC Recorder, 2002). Requirements for a refuge crop, to delay development of resistance, are also a negative aspect of GE/Bt cotton production.
- Recent research indicated that the Roundup Ready system (i.e. cultivar and glyphosate herbicide treatment) exhibited a reduction in yield or net returns (Ribera *et al*., 2001).
- According to a study compiled on behalf of the World Wildlife Found, WWF, (WWF® International, 2002) the extensive cultivation of genetically engineered cotton over a period of four years in the USA has brought no appreciable reduction in the use of insecticides and herbicides.
- A number of reports indicate a decline in average quality in the USA, which is partially attributed to GE cotton as it slowed down the rate of creation and adoption of new varieties with improved fiber qualities and probably yield (ICAC Recorder, 2002).
- Concerns are addressed to cotton breeders about stagnant yields and declining quality (Lewis, 2000). Since the mid 1980's, the effort for backcrosses to obtain GE cotton has weakened conventional breeding programs, aimed at thorough gene recombination, while cotton breeding was passed to private companies thereby weakening the Public Sector. The lack of genetic diversity in commercial varieties is now considered a problem that, in part, compounds the criticism that genetic engineering limits diversity because of backcross breeding rather than forward breeding (ICAC Recorder, 2000a). Concern is expressed also about the threat of genetic shrinkage related to the wide spread use of relatively few GE cotton varieties.

However, farmers are still confident with transgenic cotton, as it is widely acknowledged that conventional technology alone cannot meet the future needs of food, feed and fiber. Therefore, biotechnology in conjunction with conventional technology may secure the increase of crop productivity and sustainability.

Integrated pest control

Following years of intensive pesticide applications, there are many cases where the efficacy of insecticides has declined gradually, resulting in increasing numbers of applications and high risk to the economic viability of the crop. Also changes in the susceptibility to some conventional and novel insecticides have been observed (Horowitz *et al*., 1998). As a result of ineffective pest control, Integrated Pest Management (IPM) aims to control insects, diseases and weeds by alternative means in conjunction with decreased use of chemicals to avoid pollution of the environment, decrease the build up of resistance, and restore sustainability in cotton growing.

The ICAC Recorder (2000b) issued a comprehensive paper on Integrated Pest Management in Cotton. The term integrated pest management is over 40 years old. Now, IPM is more commonly associated with cotton than any other crop, as the cost of complications from excessive use of pesticides pushed researchers and farmers to think of alternative approaches to pest control. According to the Food and Agriculture Organization of the United Nations, IPM is "a broad based ecological approach to pest control utilizing a variety of control technologies compatible in a pest management system". IPM is a durable, environmentally and economically justified pest control system whereby damage caused by pests is prevented through the use of natural factors and, if needed, supplemented with appropriate chemical control measures. Even though IPM is still not fully implemented in many countries, the significance of a multi-dimensional approach to pest control in cotton has increased tremendously in the last few years and is now accepted as the best approach to pest control in terms of long-term sustainability of cotton production, environmental protection, human safety and sound profitability (ICAC Recorder, 2000b).

The current trend shows that the role of IPM in the sustainable cotton production system will increase. The main components of IPM in broad terms are: cultural control, biological control, host plant resistance, and chemical control.

IPM does not exclude rational use of insecticides and relies on the use of damage thresholds to decide when to apply pesticide products. The category of host-plant resistance includes genetically engineered Bt cotton and varieties resistant to certain herbicides. Bt-cotton could supply a very successful element of an integrated control strategy in countries where these varieties are allowed to be grown (organic farming excludes GM varieties). However, it must be emphasized that the continual use of Bt cotton most probably will change the biological balance of the pest complex. If a particular minor pest is suppressed for years, it may become a major pest with the changed pest control scheme, and new pests may also subsequently appear on cotton. Bt cotton has been utilized so far rather as an additional component of IPM rather than a foundation of the whole IPM system, as many would like it to be (ICAC Recorder, 2002b).

Fundamental principles of the IPM program are assumed to be the same in different countries and regions. However, generic recommendations have to be adjusted in a particular country, or even according to different areas within countries, according to the pest complex, agroclimatic conditions, varieties, growing conditions, and even target yields and farmers' capabilities (ICAC Recorder, 2000b).

In the framework of a combination of operations undertaken by the farmer to produce conditions unfavorable for pests to survive or multiply, the following practices are of importance:

- Crop rotation that interrupts the normal life cycle of a pest by changing the environment to one in which the pest cannot flourish or even survive.
- "Mating disruption", involving the use of sex pheromones and the release of sterile moths. These techniques have proved very successful in the control of the pink bollworm (*Pectinophora gossypiella*).
- Optimum plant nourishment.
- Weed-free and clean fields (cutting and incorporation of cotton stems immediately after harvest reduces bollworm and pink worm populations).
- Allelopathy for weed control.
- Crop monitoring.
- Cover crops for weed control.
- High plant populations for Verticillium wilt integrated control.
- Appropriate time of sowing, early sowing, and uniform planting to avoid late generations.
- Maximum possible period between crops in order to provide the longest host-free periods.
- Use of acid delinted seed.
- Use of biological control.
- Application of insecticides according to existing populations of harmful and beneficial insects especially for the start of sprayings (Conway and Kring, 2001). Preservation and augmentation of natural enemies is a key component of pest management programs (Kharboutli, 2001).
- Use of selective insecticides for the protection of useful insects.
- Safe and effective use of pesticides. Definition of economical thresholds. Use of insects' traps for counting insect catches. The ability to have daily state wide information on adult moth activity (e.g. for Lepidoptera) leads to improved decision-making capabilities for producers, especially on an Internet information delivery system for reporting *Heliothis* moth trap catches (Bridges *et al.,* 2001).
- Careful selection of the appropriate pesticide, dose and sprayer.
- Host plant resistance.
- Early maturing varieties (fewer applications).
- Use of specific morphological and physiological

characters e.g. nectariless and high gossypol.
- Use of insect traps for counting insect catches.

Conclusions

Sustainable cotton production demands higher level of skill than conventional production. More research is needed to provide reliable guidelines for an efficient and competitive sustainable production. The World Summit's issue in Johannesburg was that sustainability and development must be integrated and that both bioengineering and organic farming can play their own role. We believe that this issue is correct.

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