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Introduction

There are only a few countries in the world where cotton is grown under both rainfed and irrigated conditions. Assured irrigation facilities enable and encourage better use of inputs, particularly fertilizers and pesticides. This is the reason that average yields under irrigated conditions are usually double the yields under non-irrigated conditions. Under rainfed conditions, the costs of production per hectare are lower, but cost per kg of lint is higher due to lower yields. About 55% of the world cotton area has reliable/assured irrigation, 45% is rainfed/dryland farming. The quantity of water required to meet the needs of cotton plants in fields depends on many factors, including the irrigation system (flood, furrow, drip, subsurface drip or sprinkler). Methods used to assess the timing of irrigations are usually not science based, and water is often not applied in measured quantities. Improvements in both could enhance water use efficiency. Different countries have different sources of irrigation water. Assured irrigation water can come from rainwater collected and stored, sewerage water and water from rivers. The first article deals with various aspects of irrigation of cotton.

Researchers have explored various options to reduce the cost of production of cotton, and one such option is to shift to no-till/zero tillage production systems. No-till has been improved and conservation tillage includes no-till as one choice. The other two options are strip tillage and mulch tillage. According to the Conservation Technology Information Center in the USA, about 800,000 hectares, or about 16% of the total U.S. cotton area, was planted under conservation practices in 2002/03. The primary objective of adopting conservation tillage is to avoid soil erosion and degradation, which are serious problems in some countries. In addition to lowering costs, conservation tillage has many additional advantages. But, conservation tillage also has some disadvantages that could depend on the cover crop. The U.S. Government encourages

farmers through the Conservation Reserve Program to set aside land to save natural resources and in exchange for payment from the government. The second article in this issue of the *ICAC RECORDER* is on conservation tillage practices in the USA.

Australia commercialized genetically engineered (GE) cotton varieties in 1996 at the same time GE cotton was commercialized in the USA. Data from USDA show that 76% of the total cotton area was planted to GE varieties in the USA during 2003/04. However, Australia adopted a more cautious approach and slowly increased the area under GE varieties. In 2000/01, area under GE varieties was capped at 30% of the total cotton area until two-gene varieties became available. In the third article, Dr. Gary Fitt of the Commonwealth Scientific and Industrial Research Organization of Australia critically reviews the introduction of Ingard® technology in Australia and the impacts this has had on producers, researchers, and the industry as a whole. According to Dr. Fitt, pesticide use against *Helicoverpa* spp. was significantly reduced due to GE cotton in Australia, and the most consistent winner from the Ingard® technology has been the environment, with reduced pesticide loads. The current season (2003/04) is a transition year, with Bt varieties occupying 40% of total cotton area, made up of 25% Ingard varieties and 15% Bollgard II™ varieties. All Ingard varieties and the cap on transgenic area will be withdrawn after this season.

Short notes and Dialog search on fiber strength is also a part of this issue.

The world cotton researches conferences have become regular events held every four and half years, and are greatly acknowledged among cotton researchers in the world. The World Cotton Research Conference-3, held in Cape Town, South Africa from March 9-13, 2003, was a great success in

spite of a difficult political atmosphere in the world at the time of the conference. Over 300 researchers from 37 countries attended the conference. In four days, 164 papers were presented orally while 80 papers were presented as posters. Proceedings of the conference will be published and mailed in early 2004. There is a great enthusiasm among cotton researchers to continue the world cotton conferences initiated by ICAC in 1994. Brazil, Turkey and the USA offered to host the World Cotton Research Conference-4. The International Committee of the WCRC-3 met in Gdansk, Poland during the ICAC plenary meeting and decided to hold the World Cotton Research Conference-4 in the USA in 2007. The U.S. is considering a possible venue that is not expensive to researchers. More information will be available soon on the ICAC web page.

The Technical Information Section of the ICAC has published extensively on biotechnology of cotton. In the last 10 years, numerous articles have been published in the *ICAC RECORDER* and many papers were presented at ICAC technical seminars, organized during plenary meetings every year. The ICAC staff also made presentations at various forums in addition to launching extensive review articles. ICAC constituted an expert panel on biotechnology of cotton in January 2000 to put up a report for the ICAC. All this information, except the review articles, is available free on the ICAC web page at <http://icac.org/icac/english.html>. Developments are coming so fast in this field that the ICAC has decided to reconstitute the expert panel on biotechnology to update the report and also include issues not covered in the previous report. Dr. Gary Fitt of the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia will chair the panel, other members are included from five countries. The Panel will prepare a report for the 63rd Plenary Meeting of the ICAC to be held in Mumbai, India from November 28 to December 3, 2004. The report will be available free late next year in printed form and will also on the ICAC web page.

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Irrigation of Cotton

Water is a substance that can be recycled and brought into use again and again. According to Kandiah (1997) nearly 1,400 million km³ of water is available on the earth. This quantity can be neither increased nor decreased. It is estimated that 110,000 km³ of precipitation is received during a normal year, but almost the same quantity evaporates back into the atmosphere every year, leaving only about 40,000 km³ of water for use, most of which flows into rivers and is used in agriculture. Additionally, 3,500 km³ is captured and stored in dams and reservoirs available for agricultural uses.

The availability of water in such a huge quantity on the earth indicates that water is available in abundance. However, unequal distributions of rainfall, pollution and degradation have brought water scarcity to many countries. Current analyses suggest that the water situation in the world in general is worsening, in terms of both quantity and quality, largely as a result of poor water allocations, wasteful use of water and pollution, particularly in the agriculture sector. The largest demand for freshwater comes from the agriculture sector, and it is commonly remarked that agricultural use of water is a relatively low-value use with minimum efficiency. Water use in agriculture is also the most subsidized use of water. Such a situation requires that in case the demand for water increases, the agricultural sector would be the first to lose its allocation of fresh water.

This article discusses the irrigation of cotton and the environmental implications of inefficient irrigation in a world in which water resources are increasingly in demand. The case of the Aral Sea illustrates the stakes involved, not only for the environment but for cotton farmers and regional economies.

Irrigation Disaster

The Aral Sea in Uzbekistan, once the fourth largest lake in the world, has dried out because of the over-allocation of water to cotton production. The Syr Darya and the Amu Darya between the former Soviet Central Asian republics of Uzbekistan and Kazakhstan used to feed the Aral Sea. But in the 1960s, Soviet planners built a network of irrigation canals to divert water from Syr Darya and Amu Darya to cotton fields in Uzbekistan and other cotton producing republics. Consequently, the Aral Sea did not get enough water and started shrinking. In 1960, the Aral Sea covered 42,244 square kilometers. It is estimated that between 1960 and 1989 the lake volume decreased by 75% and the shoreline receded up to 120 km from its former extent. In fact, the Aral Sea shrank so much it is no longer a sea—it split into small parts.

The collapse of the Aral Sea is one of the most serious disasters of cotton related irrigation systems in the world. The lake was traditionally rich in salts, and the drying of the lake contributed to the elimination of fisheries businesses in the area. In addition to adding drifting salts to the atmosphere, the sea's shrinkage has also changed the climate in the area. The climate around the sea has become more continental, with shorter, hotter, rainless summers and longer, colder, snowless winters. The growing season has been reduced to an average of 170 days, fewer than the 200 frost-free days needed to grow cotton successfully. Desertification and high salt levels have destroyed the local fishery and agricultural businesses.

In response to this environmental and economic catastrophe, since 1995 the United Nations Development Programme (UNDP) has been running an Aral Sea Program that focuses

mainly on water resources management, small business development, humanitarian assistance and social and health programs in the affected areas. A number of other programs have also been undertaken in the Aral Sea area to assess the environmental impact.

The mechanisms whereby faulty irrigation practices contribute to environmental degradation are well known. Leaching and evaporation are genuine losses, but many other losses of irrigation water can be either minimized or avoided. According to FAO, most irrigation systems in the world have an efficiency of about 50%. In other words, almost half of the water is lost in distribution and application. Although it is true that the loss is not a "true" loss, as most of such water returns to irrigation streams or reaches groundwater, the water carries along with it agrochemicals including pesticides and thereby contaminates groundwater. In the field, the cotton plant takes up nutrients while the water is seeping through the root zone, but some nutrients are carried through the root zone to the groundwater.

Another source of contamination involving irrigation water is evaporation, which can bring salts to the soil surface. Just as salts can travel downward, they can also travel upward and create salinity conditions that render lands unfit for cultivation. The experience with the Aral Sea in the former USSR countries shows that continuous draining of water from lakes could be devastating for the ecosystem.

Irrigated Cotton Area in the World

Cotton is a crop of warm climate and requires a regular supply of water, either natural, in the form of rainfall, or assured, through canals from above-surface resources and/or from underground. The rainwater collected in reservoirs can also be channeled to cotton fields. Although cotton is not a water loving plant, it does require a regular supply of water for maintaining growth and balance between vegetative and reproductive growth. Lack of soil moisture, which prevents the root from absorbing nutrients and water, has serious consequences, affecting growth, leaf area index, branches, node length and more. If the plant is seriously suffering due to lack of water, even the already-formed small bolls may be shed, while the large bolls may be forced to open premature, thus producing immature and weak fiber. The water-stressed seed may also have poor germination and lower oil contents.

Countries grow cotton under irrigated conditions, rain-fed conditions and a combination of irrigated and rain-fed conditions. About 55% of the world's cotton area has reliable irrigation; 45% is rain-fed.

Water Sources

The major source of water in the world is rivers regulated by reservoirs that feed farms via canals. In many countries, particularly India, Pakistan and Uzbekistan, and parts of China (Mainland), rivers are fed by melting winter snow. Thus, the amount of snow in winter is responsible for seasonal variation in the supply of irrigation water available for cotton. Rains

Irrigated Cotton Area in Various Countries		
Country/Region	Area in Percent	
	Irrigated	Non-irrigated
Argentina		
Northeast	-	100
Northwest	10	90
Australia		
New South Wales	96	4
Queensland	83	17
Bangladesh		
Central, SW & North	25	75
Southeast	-	100
Benin		
North	-	100
South	-	100
Brazil		
Northeast	10	90
Centralwest	3	97
Burkina Faso	-	100
Chad	-	100
China (Mainland)	94	6
Colombia	10	90
Cote d'Ivoire	-	100
Ecuador	-	100
Ethiopia	70	30
Egypt	100	-
Greece	91	9
India	30	70
Iran	90	10
Israel	98	2
Kenya		
Lake Basin	10	90
Madagascar	3	97
Mali	-	100
Mexico	100	-
Myanmar	9	91
Namibia	15	85
Pakistan		
Punjab	100	-
Sindh	100	-
Paraguay	-	100
Senegal	-	100
South Africa		
Marble Hall	40	60
Spain	95	5
Sudan		
Gezira	100	-
Rahad	100	-
Halfa	100	-
Syria		
Deir-Rakka (E)	100	-
Hama-Aleppo	100	-
Hassakah (NE)	100	-
Tanzania		
Western	-	100
Thailand	-	100
Togo	-	100
Turkey	92	8
Uganda	-	100
USA	80	20
Vietnam	10	90
Zambia	2	98
Zimbabwe	6	94

during the season are important in most West African countries, India and some parts of China (Mainland), but rains during the off-season are important in other countries such as Australia. Monsoon rains have a drastic effect on production in India, where 70% of cotton area does not have an assured irrigation water supply. Excess monsoon rains could also prove to be detrimental, as is usually the case in Pakistan, where every fifth year is believed to have above normal monsoon rains, resulting in lower yields. Lower yields under such conditions are related to flare-ups of sucking pests and an inability to spray fields because of wet conditions. Cloudy and wet conditions help bollworms to become established in the greater vegetative growth triggered by rain. Flooding due to rains can also wipe out large areas.

Egypt has a unique system of irrigation in which the water supply is almost constant every year. The Gezira Scheme in Sudan, the largest cooperative farming operation in the world under one management system, has its own canal system. Many countries depend entirely on rains to start planting cotton. One such example is Burkina Faso, where planting is started only after 45mm of rain has fallen. Usually, 45mm of rainfall is received by May 20 and, if not, planting has to be delayed in order to have sufficient moisture in the ground for optimum germination. Planting when the rainy season continues, could also be risky due to crust formation and resulting poor germination. In Zimbabwe, as in other countries in the region, rains start in the beginning of summer, typically in November, and continue through to March, although some limited rainfall may also be received during April. The southern shift of the Inter-tropical Convergence Zone, a low-pressure system that moves south and north with sun, brings rain. Rainfall varies from 500mm in the low-lying dry areas to 900mm in better areas in most seasons. A month-long dry spell occurring during fruit formation before rains start again also characterizes rainfall in Zimbabwe. Thus, rains are important not only at any one particular stage of the crop or year but more than once during the season.

Countries like Uzbekistan and many other central Asian cotton producing countries do not have to wait for rain and moist ground for planting cotton. Rather, melting snow already has more than enough moisture in the ground in April, so these countries have to wait for the field to dry so that big clods are not formed when fields are cultivated for planting. Waiting also allows soil temperature to increase to levels optimal for germination.

Irrigation Methods

Cotton can be irrigated in various ways. Irrigation methods can determine not only the quantity of water used for realizing maximum water use efficiency, but also cotton yield and quality. Many countries grow cotton under rain-fed and assured irrigation conditions at the same time. Data show that the average yield under rain-fed conditions is always less than that of irrigated conditions. In most cases rain-fed cotton yield are only half those of irrigated cotton.

Over-irrigation of cotton is also undesirable. In areas where cotton survives on rainwater, rains exceeding 15-20 centimeters at one time, or even less rain but at frequent intervals can result in suffocation of the root system. Cotton is more sensitive to oxygen than most other crops and cannot survive without pore spaces in the soil. In case rains exceed soil threshold levels (depending on the soil type and interval between rains), it is important to drain standing water, particularly when rains are followed by sunny hot days. Standing water can lower oxygen levels to less than 8% in the root zone, inducing wilting from suffocation. If the cotton plant is able to survive frequent heavy rains or unnecessarily frequent supplies of irrigation water, the plant can react by producing excessive vegetative growth, thus delaying crop maturity, aggravating fungal diseases, and producing immature and weak fiber.

A shortage of irrigation water can retard growth, and small nodes cannot be enlarged once they are formed. Thus, it is very important that the water supply remain consistent for as long as irrigation is required. Although irrigation water has the potential to quickly fix some of the problems occurring due to water shortage, the effects on the plant of irrigation or rains are numerous, and most of them are irreversible. Continuation of irrigation at crop maturity when it is no longer required by the plant can delay leaf shedding and thus boll opening, and increase trash content if cotton is picked by machine. Unwanted irrigation at maturity can also induce regrowth.

Country/Region	Irrigation Systems			
	Flood	Furrow	Sprinkler	Drip
Argentina				
Northwest	5	4	1	
Australia		90	1	1
Bangladesh				
Central, SW & North	20	5		
Brazil		< 1	10	
China (Mainland)	60	30	2	2
Ethiopia	14	16		
Egypt		> 99	< 1	
Greece		6	65	20
India	20	10		
Iran	45	45	< 5	
Israel			10	88
Kenya				
Lake Basin		8		
Mexico		100		
Myanmar	1	8		
Namibia	15			
Pakistan				
Punjab	70	30		
Sindh	68	30	2	
South Africa				
Marble Hall	1	34		5
Spain		45	20	30
Sudan		100		
Syria				
Deir-Rakka (E)	25	70		5
Hama-Aleppo	20	65		15
Hassakah (NE)	30	60		10
Turkey	9	78	5	
USA	1	50	28	1
Vietnam	2	8		
Zambia			2	
Zimbabwe		2	4	

Effect of Sprinkler Irrigation on Yield and Quality

A lot of literature is available on the negative effects of sprinkler irrigation on cotton yields, though certain conditions such as sandy soils or uneven ground require the use of sprinkler systems. Water sprayed above the canopy on open flowers can interrupt flower fertilization, causing flower drop due to poor or no fertilization and a subsequent reduction in yield. According to Ontai and Bordovsky (2002), about 400,000 hectares are planted to cotton in the High Plains of Texas, USA, and most of it is irrigated by central pivot systems with above-canopy spray nozzles. They compared irrigation by central pivot system applying water 96.5 centimeters above the bottom of furrows, 30.5 centimeters above the bottom of furrows (spray below canopy) and drag sock type applicator (low-energy precision application-LEPA) and concluded that above-plant canopy application of water reduced yield by 10% compared to the other two methods. However, there was no effect on fiber quality.

Sprinkler irrigation affects yields by interfering with pollination, which begins as soon as the flower opens and anthers shed pollen grains. However, pollen tube growth and successful fertilization take time. Until then, the fertilization process is liable to be affected by conditions surrounding pollen tube growth and their attaining proper length to reach ovules. Thus, the time of the day at which above-plant canopy irrigation takes place is important. Flowers continue to be formed every day during the flowering period, and the most damaging time is when pollen grains have just begun to form pollen tubes. The safest time is when pollination as well as fertilization has been completed in the day's flowers.

Cost of Irrigation Water

Water may be expensive or cheap, but cost of production data from countries where cotton is grown under assured irrigation and rain-fed conditions with similar production practices show that it is more expensive to produce a kilogram of lint under rain-fed conditions. Total cost of production per hectare is high under irrigated conditions because irrigated cotton usually receives heavier technological inputs such as fertilizers and pesticides, but yields are much higher, which reduces the cost per kg of lint.

Irrigation water is not available in unlimited quantity. Thus, whatever is available must be used carefully to get the maximum benefits. Rainwater is free but storage, pumping and channeling it to cotton fields have a cost.

Drip irrigation is the most expensive system, but it is also expensive to irrigate fields with sprinkler systems. Canal water is also free or heavily discounted in countries like Egypt, Pakistan and Northern India, where only a service fee is charged for maintaining canal systems. Data from countries where cotton is primarily irrigated show that it is most expensive to irrigate cotton in Syria, where on the average almost 50 cents

Cost of Irrigation in Various Countries

Country/Region	Cost/Ha (US\$)	Cost/Kg Lint (US\$)
Argentina		
Northwest	36.0	0.06
Australia	35.0	0.02
China (Mainland)		
Yellow River Valley	54.4	0.04
Egypt	60.0	0.07
India		
North	17.0	0.03
Iran	110.8	0.19
Israel	530.0	0.29
Pakistan		
Punjab	141.1	0.19
South Africa		
Marble Hall	74.4	0.07
Syria	600.0	0.49
Turkey		
Aegean	70.0	0.06
Cukurova	86.5	0.07
USA		
Fruitful Rim	113.7	0.10
Zimbabwe		
Commercial Irrigate	118.4	0.10

are spent on irrigation to produce one kilogram of lint. Irrigation of cotton is least expensive in Australia due to free rain water but also due to high lint yields.

Increasing Water Use Efficiency

The water use efficiency of cotton must be improved if water used to grow cotton is to be minimized. Of course, varieties can be developed which require less water for growth, but water losses must be reduced through more efficient practices. In general, the quantity of water required to meet needs of the cotton plant in the field depends on many factors, including the irrigation system (flood, furrow, drip, subsurface drip or sprinkler). Surface irrigation is the least efficient irrigation method, drip irrigation the most efficient, and sprinkler irrigation somewhere in between. Relative costs of various types of irrigation systems will depend on many factors, but in general it is less expensive to install surface irrigation. The cost will go up many folds in subsurface irrigation. Sprinkler irrigation may be even more expensive. Irrigation by LEPA would be the most expensive; thus it is recommended for only large-scale production of high-value crops. LEPA system nozzles are positioned close to the ground, usually no more than 45.7 centimeters above the furrow, which provides minimum water runoff and high irrigation efficiency.

The quantity of water applied at each irrigation and the frequency of irrigation will determine the total quantity of water applied throughout the season. Different soil types and irrigation methods plus weather conditions require different irrigation intervals. However, drip and sub-surface drip irrigation require the least quantity of water to grow cotton. Water use

efficiency can be characterized as crop yield per unit of water use. In arid and semi-arid climates, short irrigation intervals are necessary to ensure adequate water use efficiency and optimum yield. The methods used to assess the time of irrigation are crude, and a measured quantity of water is not applied. Improvements in irrigation and measurement methods could improve water use efficiency and reduce the demand for water used in cotton production.

The World Bank undertook on-farm water management programs in a number of countries to minimize losses of water while it is carried to the field. The significant benefit of improved water use efficiency is improved environmental health as a consequence of greatly reduced runoff of irrigation tail water into rivers and streams and the associated reduction of nutrient and pesticide contamination of water. In the following section are described some success stories in Australia and Israel that could serve as catalysts for improving water use efficiency elsewhere.

Irrigation of Cotton in Australia

Cotton is grown mainly in two states in Australia, New South Wales and Queensland. Together these states contribute about 97% of national production. On average 92% of the cotton area is irrigated in both states. Cotton was grown on 400,000 hectares in 2001/02 (Goynes and McIntyre, 2003), which leads to the estimate that 12% of the water used in irrigated Australian agriculture was consumed by cotton. Rainwater is collected for irrigation purposes and the availability of water is the single most important factor determining the area to be planted to cotton. All run-off water on farms is collected and reused for irrigation. Thus, extremely dry weather during the last two seasons has reduced the area planted to cotton in Australia to around 175,000 hectares in 2003/04.

According to Schulzé (2002), in Australia one megaliter of water is used to produce one bale (227 kg) of lint per hectare. In comparison, data show that one megaliter of water produces 139 kg of lint in California, 136 kg of lint in Egypt and only 50 kg of lint in Pakistan. Research in Australia has shown that the quantity of water can be reduced to 0.8 megaliters to produce 227 kg of lint. Eight tenths megaliters is equivalent to 80 mm or 8.1 centimeters of water per bale/hectare. This means that in Australia, cotton uses less water than any other agricultural crop and produces more value per megaliter of water than any crop except the horticultural industry. How is this accomplished?

Goynes and McIntyre (2003) have reported on a project going on in Queensland to develop better irrigation water use efficiency through better application of irrigation principles. Moreover, most cotton in Australia is irrigated by the furrow method, and farmers can use scheduling tools to determine when and how much water to apply so that most of it is taken up by the cotton plant. Cotton soils are self-mulching clays and have the capability to store large quantities of rainfall water. As a result, cotton utilizes up to 85% of the water applied in each irrigation.

Irrigation of Cotton in Israel

Israel is a small cotton producing country, but it has a unique system of irrigating cotton. Water is very expensive, and most of what is available is saline and unfit for irrigation. Israel used to grow cotton with and without irrigation but since the early 1980s cotton, both upland and extra-fine varieties, is grown only under irrigated conditions. The shortage and high cost of fresh and underground water has triggered utilization of filtered sewage water. Sewage water from cities is carried to purification plants and recycled to secondary and tertiary degrees for agricultural uses. Cleaned sewage water is said to contain 20-30 ppm nitrogen and also some phosphate and potassium. It is claimed that clean sewage water is capable of adding 80-100 kg of nitrogen per hectare, almost eliminating the need for any additional nitrogen applications.

The sewage water normally undergoes four cleaning processes. The primary treatment removes coarse organic and inorganic solids, grease and oils by screening, settling and floatation processes. Microorganisms are used in the secondary process for decomposition and oxidation of complex organic matter. After these two processes, the water is safe to be used for irrigating cotton but not food crops, which require further processing. Most cotton is drip irrigated, which is very efficient, and about 5,000 meters of drip pipes are required for one hectare. Drip irrigation systems are manufactured locally, and a normal life for a system in the field is about ten years. The initial cost of system installation is of course high (estimated at over US\$ 2,000/ha) but it saves on nitrogen applications and gives higher yields.

Commonly Used Terms in Irrigation

Most terms used in irrigating cotton are common among countries. Rogers et al (1997) and others have defined some commonly used terms as follows:

Application Rate

Water can be applied to crops at various rates. The amount of water applied per hour or per unit time in inches or millimeters is called the Application Rate.

Crop Water Requirement

Crop Water Requirement is the amount of water used by the crop during a particular period. Crop water requirements change depending upon weather conditions.

Field Capacity

Field Capacity is the maximum amount of water that a particular soil can hold. Soil scientists measure Field Capacity as the ratio of the weight of water retained by the soil to the weight of dry soil.

Water Application Efficiency

A crop may not be able to use all the water delivered because some may not be within the reach of the root system. The percentage of water available (to a crop) to the water delivered to the field is called Water Application Efficiency (E_a). Losses can come from runoff, evaporation and deep percolation. Water

Application Efficiency can be high or even 100% and still a crop may suffer losses due to water shortage if the soil profile is not properly filled during irrigations.

$$E_a = 100 (W_c / W_f)$$

W_c = Water available for use by the crop

W_f = Water delivered to field

Water Conveyance Efficiency

All the water released from a source may not be delivered to fields. Losses are the highest in canal systems particularly if they are not lined. Water Conveyance Efficiency (E_c) is the percentage of source water that reaches fields.

$$E_c = 100 (W_f / W_s)$$

W_f = Water delivered to field

W_s = Water released from source

Water Distribution Efficiency

Water Distribution Efficiency (E_d) is the percentage of the average application depth delivered to the least-watered part of the field.

$$E_d = 100 [1 - (y/d)]$$

y = Average absolute numerical deviation in depth of water stored from average depth stored during irrigation.

d = Average depth of water stored during irrigation.

Water Distribution Uniformity

The percentage of average application amount received in the least-watered part of the field is called Water Distribution Uniformity (U_d).

$$U_d = 100 (L_q / X_m)$$

L_q = Average low-quarter depth of water infiltrated (or caught)

X_m = Average depth of water infiltrated (or caught)

Water Use Efficiency

Water Use Efficiency (E_i) is the percentage of water beneficially used by the crop to the water delivered to the field.

$$E_i = 100 (W_b / W_f)$$

W_b = Water used beneficially

W_f = Water delivered to field

Conclusion

A shortage of irrigation water is a common complaint throughout cotton producing countries, including both, irrigated and rain-fed cotton areas. However, misuse or inefficient use of irrigation water is equally common. There is a need to increase water use efficiency by assessing the time when irrigation is required and also by applying water in the right quantity. Many countries in which farmers get water at regular intervals have no choice, but if water is available when farmers wish, it must be timed so that the crop does not suffer due to a lack of water or too much water thus affecting water use efficiency.

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Conservation Tillage in the USA

Cotton is grown in a variety of soil types, and cultivation of vulnerable fields either by tractor or bullocks enhances the chances of soil erosion. Fortunately, vulnerable soils do not exist in all cotton producing countries. However, such soils are found in parts of Latin America, Africa and the USA. With tillage-related erosion damage reaching tons per hectare, millions of hectares could be saved from degradation and erosion if farmers practice appropriate tillage methods.

There are several options for farmers wishing to employ soil conservation practices. Although the no-till production system is extreme, conservation tillage and reduced tillage systems

provide other choices. The purpose of this article is to discuss conservation tillage in the United States, including background information advantages, disadvantages, associated practices and effects. The US Conservation Reserve Program will be described.

Background

Researchers at the University of Auburn, USA started researching the idea of conservation tillage in the 1970s by planting cotton in standing clover with the objective of saving on nitrogen fertilizer. This idea evolved into a production

system now called conservation tillage.

Conservation tillage can be defined in many ways, but one commonly accepted definition is a tillage and planting system that leaves at least 30% of the soil surface covered by residue after planting (Reeder, 2000). Thus, conservation tillage is an approach, or system, of growing crops that involves the least soil disturbance. Parvin et al. (2003) consider conservation tillage to be a production system with limited seedbed and minimum soil disturbing operations. The production system is built around chemical cultivation after emergence and maintenance of old seedbeds.

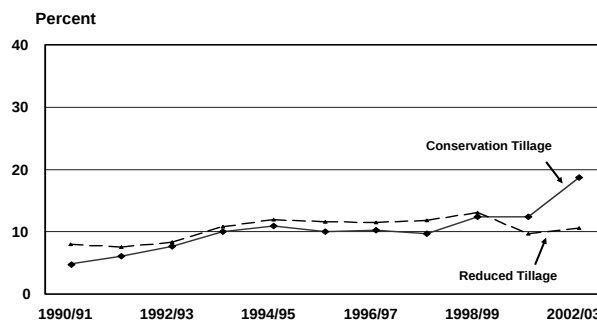
Conservation tillage may take several forms: no-till/strip-till, ridge-till or mulch-till. No-till is a system of producing crops in which soil is left undisturbed from harvest to planting except strips. Parvin et al. (2003) defined no-till as a system in which soil is not disturbed except to repair damage done during a wet harvest season or to rehip the seedbeds when absolutely necessary. All weed control operations are by herbicides. The same is true for ridge-till, but ridges are rebuilt during row cultivation. Mulch-till involves no cultivation from harvesting until just before planting, when one or more tillage operations can be undertaken to work the soil for planting or even after planting. A fourth form, reduced-till, cannot be regarded as a form of conservation tillage if the residue does not cover at least 15% to 30% of the ground. (1)

Worldwide, manual/zero tillage technology is primitive and has been followed in every country. It is assumed that many countries have at least some area under conservation or reduced tillage, particularly if cotton is grown in a mono cropping system. However, no concrete statistics are available. For example, the idea of zero tillage started gaining ground in Brazil over 20 years ago in the state of Goias, Cerrado region. It is believed that about four million hectares were planted under conservation tillage in this region, but how much of it was under cotton is not known. At the national level, Brazil had over 12 million hectares under conservation tillage. Argentina and Australia each produced about nine million hectares of no-till and or conservation tillage crops.

Conservation Tillage Area in the USA

Estimates of the area of the USA under conservation tillage vary. According to a press release issued by the Conservation Technology Information Center in November 2002 based on the 2002 National Crop Residue Management Survey, about 1.1 million hectares of cotton were planted with conservation tillage in the USA in 2002/03. This was 19% of the total area planted to cotton in 2002/03 in the USA. Nearly fourteen percent of this was planted under no-till, 3.3% under ridge-till and 1.5% under mulch-till. Reduce tillage area was 10.6%, while conventional practices and residue covering less than 15% of area occupied 71% of total area. Some other reports indicate

CONSERVATION AND REDUCED TILLAGE COTTON AREA IN THE USA



higher levels of conservation tillage. The area under conservation tillage varies among states from less than 1% in California to over 30% in Georgia.

Advantages and Disadvantages of Conservation Tillage

Conservation tillage has numerous advantages as well as some disadvantages. Conservation tillage can benefit crop growth and yield in many ways, both directly and indirectly. The main advantages of conservation tillage are:

- Conservation tillage increases soil water infiltration rates and decreases runoff.
- The crop residue mulch on the soil surface improves moisture conservation. This enhances crop growth and shortens the time period before canopy closure of cotton. Thus, evaporation and evapotranspiration rates are reduced while the crop intercepts more light.
- Conservation tillage typically reduces machinery trips in the field. This has the potential to reduce fuel, labor and repair and maintenance expenses.
- Conservation tillage reduces soil compaction and soil erosion because it requires fewer field trips by tractors and other implements, thus having a positive impact on yield.
- Conservation tillage permits early entrance into fields and also requires fewer days suitable for field work, allowing for earlier planting in poor spring weather. Both factors jointly promote early planting and thus early maturity.

Conservation tillage has some disadvantages as well:

- Non-cultivation of conservation tillage fields for a long time encourages weed growth. The intensity of perennial weeds increases, and herbicide use becomes necessary. Thus, where herbicides are already used, the quantity of chemicals to be used may increase. This is why the introduction of herbicides like Roundup Ready has

(1) According to the Conservation Technology Information Center, a national, nonprofit public-private partnership working to promote soil and water quality and equip agriculture with affordable, integrated management solutions, reduced tillage is a system of farming where residue covers 15-30% of the area.

stimulated the adoption of conservation tillage in the USA.

- Conservation tillage with minimum cultivation practices may encourage new dynamics among soils, pests and diseases that may require development and introduction of new species. The cooler soil temperatures and higher soil moisture associated with conservation tillage could increase the incidence of soil-borne seedling diseases.
- Conservation-tilled fields ready to be planted with cotton can have weeds, even at the time of planting. It is possible that insects may become established on weeds and that when weeds are removed, particularly in Roundup Ready transgenic cotton, insects will move to cotton.
- It is a challenge to handle the crop residue, which can be huge in the case of some cover crops. Residue may also be difficult to get rid of if, like rye, it grows tall. In some cases nitrogen application may be recommended prior to planting cotton for faster decomposition of the crop residue.
- Continuous no-till will result in the upper one to two inches of soil becoming acidic much faster than under conventional, deep tillage. The soil pH can go down and affect yields unless appropriate measures are taken to neutralize acidity created by fertilizers, ammonium containing.

Lower Cost of Production

Although soil erosion is not an issue on flat, loose soils, conservation tillage has the potential to lower the cost of production, though not under all production systems. The effect of conservation tillage can be quite pronounced and economically justified. On the other hand, the effect can be only a marginal increase in yield, or even no increase in yield, but with a lower cost of production compared to conventional practices.

Cooke *et al.* (2003) compared three production systems: 1) no-till solid planting at one meter (40 inch) row spacing under dryland conditions, 2) no-till solid planting at one meter row spacing under irrigated conditions, and 3) one skip row after every two rows under dryland conditions. No tillage operations were performed from harvest of one season, i.e. October/November 2001 and during the season in 2002/03. All ground application of inputs was made in the middle of two rows or in 50 centimeter bands over the terminal of the plant only. Two

applications were made by ground but others were made from the air. There are some exceptions to the data, but the overall conclusions are that dryland solid and irrigated production systems produced almost the same yield. Skip row planting produced a lower yield, which could have been due to dryland conditions, as the plant may not have been able to gain proper volume for bearing the required number of bolls. Although these yield data suggest that skip row is not suitable for no-till production systems, the net return proved the opposite because of lower production costs. A conventional dryland solid planting production system was not included in the trial, but the data taken from a comparable source indicated that in the Mississippi Delta, no-till was economically better under all three production systems compared to conventional practices. The trial is planned for a number of years, and the data in ensuing years may prove the economic advantage of no-till dryland in solid or skip row versus other production systems.

Multi-year trials conducted in Louisiana and Mississippi by Ferguson and Bradley (2003) proved that no-till produced higher yields at lower costs of production than conventional practices. Experimental sites called "Centers of Excellence Farms" were selected in 1998, and an average of the data for five years showed that the no-till production system had an economic advantage over traditional production practices. Ferguson and Bradley (2003) compared no-till, low-till and conventional practices in replicated trials on a plot of about 24,000 square meters for the first three years and about 18,000 square meters in 2001/02 and 2002/03. The cost of production in no-till production system in the Mississippi trial was lower by US\$ 63/hectare over the conventional system. The low-till system cost was also lower than the conventional system, but by a margin of only US\$27/hectare, and most of the difference was due to tillage and harvesting costs. Although the data varied among years, yields were higher in no-till than other production systems. Lower production costs and higher yields in the no-till system gave a net advantage of US\$138/hectare over conventional systems. The Louisiana location also showed the same savings in cost of production for no-till versus the conventional system. The low-till margin over the conventional system was slightly higher, reducing the difference between no-till and low-till systems. Compared to Mississippi trials, the Louisiana locations resulted in higher overall profit in no-till over conventional practice.

Martin *et al.* (2003) found that not only the cost of production of variable cash expense was lower in no-till production, but also the fixed cost was significantly lower. They presented data for three different farm sizes, 404 hectares, 808 hectares and 1,212 hectares and found an almost 50% reduction in the cost of equipment, including tractors, cultivators, hippers/bedders, row conditioners, disks and subsoilers. Even if the farm is only partially elevated to no-till or conservation

Comparison of Four Production Systems in Mississippi, USA - 2002/03

Production System	Lint Yield (Kg/Ha)	Cost of Production (US\$/ha)	Net Return (US\$/Ha)
No-till, solid, dryland	950	1,197	62.3
No-till, solid, irrigated	944	1,248	4.6
No-till, 2x1 skip row, dryland	886	1,096	79.9
Conventional, solid, dryland	925	1,394	-166.1

tillage, the cost of equipment and other fixed items will be significantly reduced.

Cover Cropping

The use of conservation tillage necessitates the use of cover crops, weed control via herbicides and insect control. Cotton or any other main crop planted following conservation tillage practices protects fields from erosion, but only during the crop season. Cover crops are planted during the off-season to protect soil from erosion caused by wind and water. Cover crops also enhance organic matter, improve soil texture and add nitrogen in addition to some other nutrients. A number of choices are available to farmers, but depending upon soil types and growing conditions, the selection of a suitable cover crop can bring additional economic benefits.

Leguminous crops, which are able to fix nitrogen in the soil, are in some respects more attractive than non-legumes. Various legume crops have been tried as cover crops in the USA. It is attractive to plant legumes as they can offset the cost incurred in planting through additional provision of nitrogen. However, legumes also pose problems: they are hard to kill, cause difficulty in having a good stand of plants, cause delay in crop maturity and may have a negative effect on yield. Also, they may not provide as well organic matter as some other crops.

Both the amount of nitrogen that has been fixed by the cover crop and when that nitrogen will be available to cotton are important considerations in deciding which leguminous cover crop to use. Nitrogen fixed by leguminous crops will be available to cotton early in the season, which may or may not be desirable and can contribute to excessive vegetative growth. On the other hand, decomposition of the cover crop residue can also be a consideration for farmers. Some materials may enhance the activities of undesirable microorganisms and other pests like termites, as is the case in green manuring prior to cotton. The objectives of green manuring and cover cropping can be different, but they will have the same effects on soil and cotton. However, it is not necessary that cover crops have a direct effect on cotton yield.

The addition of nitrogen with cover crops increases the need to evaluate nutrient requirements of the commercial crop and also carry out soil testing for proper fertilization during the season. Therefore, it is important to assess soil conditions with respect to nutrients like P and K prior to planting the cover crop and to add fertilizers accordingly. Soil scientists also recommend that soils be sampled from two different depths to get a better idea of conditions. However, immobile nutrients like P and K cannot be added during the season due to the inability to work them in the soil in conservation tillage or no-till farming. Nitrogen is not a problem and can be adjusted during the growth period. However, some cover crops may require up to 25% more nitrogen due to immobilization or tie up of soil nitrogen by the decomposing cover crop residue. Leguminous cover crops may change fertilizer timing in cotton.

A non-leguminous crop such as rye can be a better choice under sandy soil conditions. Schomberg et al (2003) studied the effect of strip tillage and no-till and six cover crops under coastal plain soils in Georgia, USA: Austrian winter pea (*Pisum sativum*); Balansa clover (*Trifolium michelianum*); crimson clover (*Trifolium incarnatum*); hairy vetch (*Vicia villosa*); seed radish (*Raphanus sativus*); black oat (*Avena strigosa*); and rye (*Secale cereale*). The effects on cotton yield, nitrogen fixation and cover crop biomass production were compared. Three-year average data show that rye consistently produced higher biomass than other crops. On average, rye produced about 4.75 tons/ha of biomass compared to 3.8 tons/ha for black clover and only 1.3 tons/ha for crimson clover. The field left uncultivated produced volunteer weeds equivalent to a biomass of 0.7 tons/ha only. The two legumes, Austrian winter pea and hairy vetch added more than 67 kg/ha of nitrogen to the soil. The other cover crops did not contribute significantly to the available nitrogen supply for cotton. Dry season planting resulted in lower vegetative mass and lower nitrogen added to the soil. All cover crops showed a positive effect on lint yield, but the differences were not significant.

If small grain crops are used as a cover crop, the cover crop should be killed at least 2 weeks before planting, which means a chemical has to be sprayed three to four weeks before planting cotton. This allows the cover crop residue to decay and also lets the soil warm for optimum germination.

Impact on Yield

The effect of cover crops on yield varies depending on growing conditions. Mitchell *et al* (2002) conducted trials on cotton and tomato in California, planting tomato in winter and a mix of tricale, Merced rye grain and common vetch prior to each summer crop season for three years. The cover crop was chopped and disked into the soil as a green manure in the standard tillage system with a cover crop, and spread on the surface in conservation tillage with a cover crop. Results showed that conservation tillage can lower yields compared to standard practices. The same is true for a cover crop; it can have a negative effect on cotton yields. This is why conservation tillage is not popular in California.

Cotton Yields under Conservation and Standard Tillage

Kg/ha Lint

Standard Tillage	
No Cover Crop	1,936
Cover Crop	1,506
Conservation Tillage	
No Cover Crop	1,722
Cover Crop	1,614

Weed Control

Weed control is extremely important in cotton, and about 95% of USA cotton area receives herbicide applications every year. Herbicides are applied as pre- and post-emergent treatments, but mechanical cultivation is also practiced to minimize herbicide use and to obtain perfect weed control.

Although farmers following intensive production practices or non-conservation practices can increase or reduce the use of herbicides and compensate with mechanical cultivation to get rid of weeds, farmers using conservation tillage do not have this flexibility. Herbicide use on cotton is critical in conservation tillage production and pre-emergence herbicides have to be broadcast because cultivation is usually eliminated in most conservation systems. In fact, conservation tillage practices may result in even more weed problems. Some weeds can be the same as in conventional production systems, but there can also be new weeds due to the cover crop. Chances are that, owing to reduced cultivation, perennial weeds may become more prevalent when using conservation tillage. The good news is that the release of herbicide-resistant varieties, particularly those resistant to Roundup Ready herbicide, has boosted the area under no-till and reduced tillage practices.

Insect Control

The impact of various conservation tillage systems will be pronounced on agronomic practices, but insect control cannot be ignored. The effect may not be drastic, but some changes are expected in the insect control requirements of cotton planted in conservation tillage production systems. Delayed maturity and an additional supply of nitrogen in the case of legumes as cover crops may increase the threat from certain pests. A longer growing season is critical to the needs of insecticide use. Late-season pests can increase in population because of the delay in maturity, though reports indicate that aphid populations increase early in the season and during peak flowering in fields with conservation tillage.

Conservation Reserve Program

The 2002 US farm bill contains a provision called the Conservation Reserve Program that allows farmers to remove environmentally sensitive land from agricultural production and get payment from the U.S. Government. The main purpose of this program is to save topsoil from erosion and conserve natural resources. Farmers enter into long-term contracts of 10-15 years with the government and in exchange receive annual rental payments and a payment of up to 50% of the cost of establishing the conservation practices. The Conservation Reserve Program has many advantages, including protecting and improving the condition of lakes, rivers, ponds and streams in addition to improving wildlife populations. Farmers voluntarily apply for the program. The program was open in May 2003 for 25 days for enrollment, and 15.9 million hectares could be accepted in the Program. The Conservation Reserve Program provision in the 2002 farm bill is not new, and previous participants were allowed to continue

in the new program effective from October 2003 or October 2004, depending upon each farmers' choice. There is a system to evaluate candidate land for eligibility in the conservation program. It is not known how much land where cotton can be grown successfully will go into the conservation program, but the program demonstrates a high level of interest in land conservation in the country. The conservation program as a whole also contains other programs such as the Grassland Reserve Program, Environmental Quality Incentive Program, Wildlife Habitat Programs, and others.

Conclusion

Conservation tillage is a tillage and planting system that leaves at least 30% of the soil surface covered by residue after planting. In the United States areas planted under conservation tillage in each state range from 1% to 30% depending on local conditions. It is an important means of conserving and improving soil and reducing costs. Disadvantages include the possibility of increased weed and pest problems, the need to use herbicides, and the possibility of reduced yields. An important program for soil conservation in the USA is the Conservation Reserve Program, in which farmers voluntarily contract to take land out of production in return for a fixed payment and partial reimbursement of costs.

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Implementation and Impact of Transgenic Bt Cottons in Australia

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Cotton is a significant primary industry for Australia with some 500,000 ha grown, producing from 700,000 tons to 800,000 tons lint annually, although in the last few years drought has severely reduced area and production. Over 90% of production is exported as raw lint making cotton the third largest crop exported from Australia. Australia is the fourth largest player in the world export market. Yields and fiber quality are among the world’s highest.

Australian cotton is attacked by a multitude of pests, with *Helicoverpa* spp. being easily the predominant problem (Fitt 1994, 2000). Historically pest management has relied largely on synthetic insecticides (Fitt 1994), although some biological approaches were also applied. The dependence on pesticide intervention brings with it several environmental and economic liabilities: development of insecticide resistance in key pests and secondary pests; reductions in beneficial insect populations with associated secondary pest outbreaks; potential for environmental contamination; and cost. Collectively these provide a strong rationale for the implementation of integrated pest management (IPM) systems, and Bt cottons as part of that.

There has been a long history of research into IPM approaches which might reduce pesticide dependence. Outcomes of this research coincided with the era of biotechnology and the introduction in 1996 of genetically engineered cottons expressing the delta-endotoxin genes from *Bacillus thuringiensis* subsp. *kurstaki* (Bt), which offered opportunities to drastically reduce pesticide requirements for the key Lepidopteran pests (*Helicoverpa armigera* and *H. punctigera*) and to implement sustainable and environmentally acceptable IPM systems. Both the Australian *Helicoverpa* spp. are naturally much more tolerant of Cry1A toxins than is *Heliothis virescens*, the main target for Bollgard cotton in the USA (Liao

et al., 2002). This difference introduces particular difficulties in achieving a high and consistent level of efficacy of Ingard® cotton varieties and certain challenges for robust resistant management strategies.

Bt cotton varieties have now been commercialized in nine countries: Argentina, Australia, China, Colombia, India, Indonesia, Mexico, South Africa and USA (James 2002). In Australia the Cry 1Ac gene from Monsanto is available in most commercial varieties (trade name Ingard®) from two seed companies, Cotton Seed Distributors and Deltapine. In this article, the introduction of Ingard® technology in Australia and the impacts this has had on producers, researchers, and the industry as a whole are discussed.

Ingard® Cotton – Phased Release

Table 1 summarizes the major field research and development stages for Ingard® Cotton leading to limited commercial release in 1996/97 and then phased introduction thereafter. Between 1992/93 and 1995/96, the field assessments involved pre-release regulatory research to establish performance and biosafety. Despite the potential benefits of Bt cotton technology and the demonstrated safety of Bt in conventional sprays, a number of potential environmental and ecological impacts required research prior to commercial release. These were addressed through a series of field and laboratory studies (Fitt *et al.*, 1994, Llewellyn and Fitt 1996, Brubaker *et al.*, 1999, Fitt and Wilson 2002), which in some cases are ongoing. Research continues on potential impacts of Bt cotton residues on soil microbes and potential weediness of Bt varieties in tropical environments of northern Australia (Eastick 2002).

The initial registration of Ingard cottons was conditional upon the development of an industry approved resistance management strategy. This process was overseen by the

Table 1: Scale of Field Assessment and Commercial Deployment for Ingard Cotton in Australia

Year	Area (Ha)	% of Cotton Area	Main Activity
1992/93	200 plants	-	Assessment of outcrossing risk and field efficacy.
1993/94	0	-	Field efficacy and assessment of outcrossing risk.
1994/95	10	-	Field efficacy and environmental impacts (non-targets, pest dynamics).
1995/96	40 (4 sites)	-	Environmental impacts and IPM performance.
1996/97	30,000	8.0	Five year registration granted and annual review. Limited commercial release by area and region.
1997/98	60,000	15.0	Limited commercial release by area and region.
1998/99	85,000	20.0	Limited commercial release by area and region.
1999/00	125,000	25.0	Limited commercial release by area and region.
2000/01	165,000	30.0	Limited commercial release by area and region.
2001/02	184,000	30.0	Capped at 30% until two gene Bt varieties become available (2003/2004).

Transgenic and Insecticide Management Strategy Committee (TIMS), with a membership consisting of cotton growers, scientists, cotton consultants and chemical industry representatives. Since 2001, the legislated Office of the Gene Technology Regulator (OGTR) has assumed responsibility for the oversight of issues with GM crops in areas of human health and environmental safety.

Ingard® registration in 1996/97 allowed for 30,000 ha to be planted to transgenic Ingard® varieties representing about 8% of the total cotton area in that year. Thereafter the area of Ingard cotton increased in 5% increments up to 30% where it was capped by the industry in anticipation of future releases of more efficacious two gene (Cry1Ac/Cry2Ab) Bt varieties. Bollgard II cotton varieties have now been released in 2003/04.

Field Performance of Ingard® cottons

Pyke and Fitt (1998) provided a summary of the performance of Ingard® cotton varieties over the first two years of commercial use and the interaction of the industry with Monsanto. Prior to release and in the first year of commercial use there were a number of unrealistic expectations of Ingard® technology, which were reinforced by the initial license fee of A\$245 per hectare. In the first year of field research in Australia, 1992/93, it was demonstrated that Bt transgenic cotton plants were very effective in controlling *Helicoverpa* larvae for much of the growing season, but did not provide season long control. There was evidence of a progressive decline in efficacy as plants matured and senesced (Fitt *et al.*, 1994). This observation set the scene for much research which followed, seeking to quantify the seasonal changes in efficacy of Ingard varieties and the environmental/agronomic factors which may influence efficacy.

Subsequent experience in Australia has confirmed that efficacy of varieties expressing Cry1Ac is not consistent through the growing season and can be highly variable (Fitt *et al.*, 1994, Fitt *et al.*, 1998, Daly and Fitt 1998). Efficacy against *Helicoverpa* spp. typically declines through the boll maturation period, to the point where survival of larvae is little different to that in non-transgenic cotton (Fitt *et al.*, 1994, Fitt *et al.*, 1998), although growth rates of survivors on the Ingard® crops are still dramatically reduced (Fitt unpublished). The decline in efficacy necessitates supplementary *Helicoverpa* control on Ingard® crops, particularly in the last third of the growing season.

Coupled with the variability of efficacy between crops, the consistent seasonal decline in efficacy has several implications. One relates to the uncertainty generated for crop managers and the confidence they may have in using thresholds for Bt cotton. Current thresholds are two small larvae/meter of row for two consecutive check dates (or one medium larva/meter on the first check). Some crops have suffered damage because consultants complied with the thresholds and left small larvae untreated; subsequent insecticide treatments failed to control

larger larvae. An unfortunate consequence is that consultants may have adopted more conservative thresholds, thereby eroding the full IPM value of Ingard® cotton.

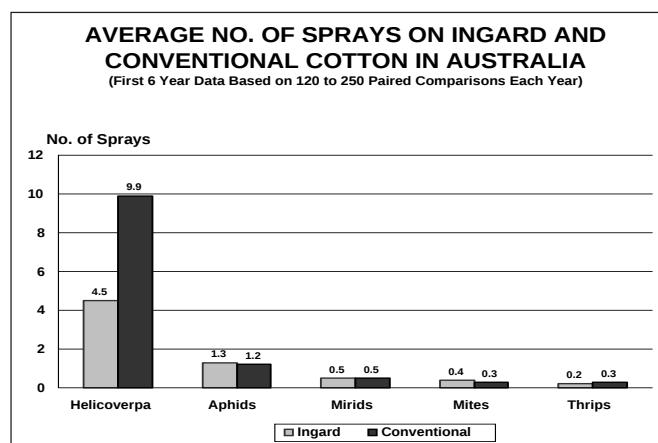
A second significant consequence of changing field efficacy is the added selection pressure that may apply on Bt resistance. The resistance management strategy in place for Bt cotton (Roush *et al.*, 1998) relies on the use of refuges, but these work best when the plants are highly efficacious and have the capacity to kill a high proportion of heterozygous resistant individuals. Ingard cotton varieties expressing a single Cry1Ac gene clearly do not express a high dose and heterozygote mortality is unlikely to be high except perhaps when plants are quite young (up to squaring phase). A significant period of selective mortality is likely during the season. Given this, the other components of the resistance management strategy are even more crucial. It is for this reason that the use of Ingard cotton has been restricted by a cap on area in the first years of commercial use. This serves to magnify the size of the total refuge that includes the refuge crops grown specifically with Bt cotton, the area of conventional cotton (at least 70% of the total) and all other *Helicoverpa* susceptible crops grown in eastern Australia. This represents a huge refuge.

Impacts on Pesticide Use

Figure 1 summarizes the average spray numbers applied to Ingard® and conventional crops for a range of cotton pests. For *Helicoverpa*, there have been consistent reductions in the number of sprays applied to Ingard® crops compared to conventional ones, averaging 56% and ranging from 43% (1998/99) to 80% (2001/02). For the minor pest groups there has been no significant change in pesticide applications after 6 years.

In 1998/99 it is estimated that the reduction in spraying across 125,000 ha of Ingard® crops resulted in 1.75 million liters less pesticide entering the environment. Despite the variable performance, the average 56% reduction in pesticide applications for *Helicoverpa* represents a spectacular impact for an IPM product.

On average the greatest reduction in sprays has been during the squaring and flowering stages of crop development (50-



67%) whereas reductions during boll filling and opening have been more modest (20-35%). Consequently the most dramatic reductions in use have been among the early to midseason pesticide groups (endosulfan, carbamates and synthetic pyrethroids). In each case this reduction has major environmental benefits.

Impacts on Economic Returns

Comprehensive information on pesticide use, yields and returns to growers is provided in reports produced by the Cotton Research and Development Corporation of Australia. Table 2 summarizes the key points from these comparative analyses around the issues of yield, pesticide use, pest control costs and economic returns. With significant reductions in pesticide applications, Ingard® cotton could be expected to provide greater returns to growers. As yet there has been no comprehensive economic assessment of the value of Ingard technology in the Australian environment, in contrast to those in the USA (e.g. Falck-Zepeda *et al.*, 2000), which show significant benefit accruing to growers.

In the 1997/98 season, Monsanto retained a license fee of A\$245 per ha, but provided rebates totaling A\$35 per ha for growers who complied with various components of the resistance management strategy. In subsequent years, the Ingard® license fee dropped to A\$185/ha with an A\$30 rebate for full compliance with the resistance management strategy, giving a net fee of A\$155/ha which has remained largely unchanged since. During the first 4 years much of the economic benefit was subsumed by the technology license fee, with the result that net economic return was similar to conventional cotton (Table 2). There was however, huge variation in returns with some growers in each year achieving gains of A\$1,000/ha while others recorded a net loss of A\$1,000/ha.

In the last two years net economic returns from Ingard varieties have been considerably higher at over A\$300/ha. This reflects the progressive improvement in varietal performance, increased experience of growers and consultants in managing Ingard cottons and the lighter pest pressure experienced in those years. Nonetheless, intangibles due to reduced environmental

impact and enhanced sustainability have not been valued yet.

Over the six years of commercial use there have been changes in the license fee, area of Ingard® grown, range of varieties available and pest pressure, all of which complicate between year comparisons. In general, average yields of Ingard® have been comparable to or higher than conventional cottons, although in the 1998/99 season, yields of Ingard® varieties were markedly lower in one region (Gwydir). There were no significant differences in crop maturity (time from planting to harvest) between Ingard® and conventional varieties in any year.

The most consistent “winner” from Ingard® technology has been the environment, with reduced pesticide loads, while the cotton industry has gained long term sustainability through the progressive adoption of more integrated pest management approaches using Ingard® cotton as a foundation.

Despite the variability of economic return implicit in Table 2, and the additional management requirements imposed on growers by Ingard cotton, it is noteworthy that all the licensed area available each year has been sold. Clearly growers attribute value to the environmental benefits associated with Ingard® cotton. Indeed some 80-90% of growers have consistently identified their prime reason for growing Ingard® cotton as “protection of the environment”. Since the 1999/2000 season, by which time expectations of Ingard® cotton were more realistic, over 70% of consultants and growers indicated they believe Ingard® cotton provided “even or better” value for money and some 80% of surveyed growers were “satisfied” with Ingard® performance.

Resistance Risk and Management Requirements

The major challenge to sustainable use of transgenic cottons is the risk that target pests may evolve resistance to the Cry1Ac protein. Resistance to conventional Bt sprays has evolved in field populations of *Plutella xylostella* (Tabashnik, 1994a,b) and the possibility of resistance is a real concern, particularly for *H. armigera* which has consistently developed resistance

Table 2: Yield and Economic Returns from Ingard and Conventional Cotton Across Australia

Year	Crop Type	Sample size *	License Fee/ha (A\$)	Rebates (A\$)	Net License Fee/ha (A\$)	Yield/ha (Kg/ha)	No. of Sprays (Total)	Av. Cost/Spray** (A\$)	Average Insect Costs/ha ** in A\$ (Range)	Net Benefit in Insect Costs (A\$)	Net Economic Benefit in A\$ (Range)
1996/97	Ingard	210.0	245.0	"Value guarantee"	245.0	1,753 (1,660-2,025)	5.0	53.0	508 (410-622)	-41.0	-262 (-409 to +68)
	Conventional					1,873 (1,796-2,127)	10.3	45.0	467 (393-635)		
1997/98	Ingard	179.0	245.0	35.0	210.0	1,910 (1,726-2,082)	6.0	49.0	491 (434-515)	-35.0	22 (-111 to +193)
	Conventional					1,901 (1,697-2,028)	10.2	45.0	456 (395-524)		
1998/99	Ingard	110.0	185.0	30.0	155.0	1,549 (1,452-1,876)	8.7	56.0	675 (418-853)	91.0	6 (-1,200 to +1,000)
	Conventional					1,676 (1,556-1,855)	14.0	52.0	766 (577-944)		
1999/00	Ingard	149.0	185.0	30.0	155.0	1,826 (1,526-2,019)	6.2	56.0	501 (414-656)	72.0	50 (-1,400 to +2,000)
	Conventional					1,810 (1,472-2,116)	10.3	56.0	573 (205-712)		
2000/01	Ingard	142.0	185.0	30.0	155.0	1,721 (1,683-1,989)	4.6	57.0	426 (279-545)	182.0	328 (-1,000 to +1,500)
	Conventional					1,665 (1,501-2,019)	9.9	61.0	608 (451-704)		
2001/02	Ingard	229.0	185.0	15.0	170.0	2,089 (1,574-2,216)	3.1	45.0	327 (260-433)	177.0	331 (-700 to +1,400)
	Conventional					1,989 (1,712-2,130)	8.6	53.0	504 (390-768)		

* Number of paired comparisons of Ingard and conventional cotton crops.

** Including net Ingard license fee.

to synthetic pesticides (Forrester *et al.*, 1993, Fitt, 1989, 1994). For this reason a pre-emptive resistance management strategy was implemented with the commercial release of transgenic varieties. The strategy adopted in Australia is targeted at *H. armigera* and based on the use of refugia to maintain susceptible individuals in the population (Roush, 1996, 1997; Gould, 1994). This strategy seeks to take advantage of the polyphagy and mobility of *Helicoverpa* spp. to achieve resistance management by utilizing gene flow to counter selection in transgenic crops.

Key elements of the strategy are as follows:

- Effective refuges on each farm growing Ingard cotton
- Defined planting window for Ingard cotton to avoid late planted crops that may be exposed to abundant *H. armigera* late in the growing season
- Mandatory cultivation of Ingard crops to destroy most overwintering pupae of *H. armigera* and a requirement to remove any volunteer Bt plants in subsequent seasons
- Defined spray thresholds for *Helicoverpa* to ensure any survivors in the crops are controlled
- Monitoring of Bt resistance levels in field populations

All elements of the Ingard® management plan are included in a printed strategy provided to all cotton growers and available on the web (<http://www.cotton.crc.org.au/Assets/PDFFiles/IMPInga.pdf>). The plan stipulates planting times and areas for refuges, necessary distances of refuge from an Ingard® crop, and management requirements for refuges.

Refuge options have been defined on the basis of ongoing research which seeks to quantify the value of different options in generating moths (Fitt and Tann 1996) and ranks potential refuges in relation to unsprayed conventional cotton, regarded as the “control” refuge. Options are expressed as the number of hectares required for every 100 ha of Ingard® cotton. Current refuge options include:

- 10 ha of unsprayed conventional cotton
- 100 ha of sprayed conventional cotton
- 15 ha of unsprayed sorghum
- 20 ha of unsprayed corn
- 5 ha of unsprayed pigeon pea

Refuges are required to be in close proximity to the transgenic crops (within 2 km) to maximize the chances of random mating among sub-populations (Dillon *et al.*, 1998). At present the conventional sprayed cotton refuge option remains most popular, although an increasing proportion of growers are now using unsprayed non-cotton refuges (40% in 01/02). Unsprayed refuges will also be used for the future extensive deployment of Bollgard II™ cottons expressing both Cry1Ac and Cry2Ab proteins.

An additional element of the conservative Australian deployment of Bt cotton was the phased introduction of

Ingard® varieties and imposition of the 30% cap of total cotton area. Bollgard II™ varieties have now been approved for commercial use and occupied about 5,000 ha in 2002/03. The two gene varieties provide much better efficacy and hence even greater reduction in pesticide requirement, but their main purpose is to provide much greater resilience against the risk of resistance (Roush 1998). The current season (2003/04) is a transition year with Bt varieties occupying 40% of total cotton area, made up of 25% Ingard varieties and 15% Bollgard II™ varieties. All Ingard varieties will be withdrawn after this season and the cap on area of transgenic will be withdrawn. This rapid transition to Bollgard II™ again reflects a commitment to resistance management in minimizing exposure of single gene Bt varieties.

All aspects of the Insect Management Plan for Ingard® and Bollgard II™ varieties are embodied in the label and are part of a single use contract growers must sign with Monsanto in order to purchase seed. Components of the resistance management plan are thus legally binding on the grower. To support this the contract and label also stipulate that each farm growing Bt varieties be audited three times each year to check on compliance with refuges, pesticide use and compulsory plowdown.

Transgenic Bt Cotton as a Foundation for IPM

Ingard and Bollgard II™ cotton varieties are not perceived as “magic bullets” for pest control in Australia. Instead they are viewed broadly as an opportunity to address environmental concerns about cotton production and more specifically as a foundation to build IPM systems which incorporate a broad range of biological and cultural tactics (Fitt 2000). Research has shown little effect of Bt cottons on non-target species, including non-lepidopterous pests, beneficial insects, and other canopy dwelling and soil dwelling species (Fitt *et al.*, 1994; Fitt and Wilson 2000; Fitt and Wilson 2002). Survival of beneficial is markedly higher than in conventional sprayed cotton, and they provide control for some secondary pests, particularly those which are induced pests in sprayed cotton (e.g. mites and aphids).

Reduced use of disruptive pesticides afforded by Bt varieties has allowed greater focus on the management and manipulation of beneficial species (Fitt 2000), through techniques for conservation and augmentation. A range of other IPM tactics can also be deployed. Indeed the last five years has seen a dramatic adoption of IPM systems (Wilson *et al.*, 2003) with reductions in pesticide use in conventional cotton varieties as well as in Bt varieties. It could well be argued that Bt varieties have allowed growers to develop confidence in the capacity of beneficial insects to play a role in pest management and so have stimulated more widespread adoption of IPM than might otherwise have been possible.

Conclusions

Ingard® cotton, as the first commercial introduction of biotechnology to the Australian cotton industry, has shown the potential of transgenic pest tolerant crops to significantly reduce pesticide use, providing major environmental benefits. After an initial period of negligible economic benefits, Ingard varieties are now returning significant economic benefits. At this time it is not clear what the license fee for Bollgard II varieties may be. Despite this growers are likely to benefit in the long term through the clear contribution of Bt cottons to sustainability. Until now Ingard cotton has occupied only a restricted proportion of the Australian cotton area. With Bollgard II™ varieties the 30% cap will be removed and substantially larger areas are likely. That Ingard® cotton has not been a “magic bullet” is fortunate in demonstrating that pest tolerant transgenic cottons will need to be introduced as part of an IPM system that incorporates a range of tactics. The deployment of Bollgard II cotton and a range of herbicide tolerant cottons will see transgenic varieties become an important cornerstone of sustainable cotton production systems for Australia.

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Short Notes

• Varieties Planted in the USA-2003/04

The latest report from the Agricultural Marketing Service of the US Department of Agriculture shows that during 2003/04, about 140 varieties were planted on a commercial scale in the USA. The Cotton Program of the Agricultural Marketing Service of the USDA undertook informal surveys of cotton ginners, seed dealers, extension agents and other knowledgeable sources to estimate area planted to each variety and published a report in September 2003. According to the report *Cotton Varieties Planted 2003 Crop*, transgenic varieties were planted on 76% of the total area. This includes Bt varieties, herbicide resistant varieties and varieties with both types of genes. Varieties with only insect resistant genes accounted for only 1.4% of the total cotton area in the USA. Stacked gene varieties having insect resistant as well as herbicide resistant genes were planted on 47% of the total area. The herbicide resistant varieties, most of which are Roundup Ready, were planted on 28% of the total area. The percentage of area under transgenic varieties varied significantly among states from 100% in Florida to 42% in California. Transgenic varieties accounted for 56% of 2.3 million hectares planted to cotton in Texas in 2003/04. Deltapine brand varieties were the most popular in the USA during 2003/04, followed by Paymaster brands. Next table shows important company brands and area planted to their varieties.

In 2003/04, the most popular variety was DP 555 BG/RR, which is as tacked gene variety and was planted on 8.7% of the US cotton area, followed by ST 4892 BR planted on 7.9% of the total cotton area. No single variety accounted for more than 10% of the total cotton area in 2003/04.

Cotton breeding in the USA is in the private sector, and many seed companies are involved. Each seed company

Brands	% Area 2003/04	Main Varieties
Deltapine	33.0	DP 555 BG/RR, DP 451 B/RR & DP 458 B/RR
Paymaster	21.3	PM 1218 BG/RR, PM 2326 RR and HS 26
Fibermex	15.6	FM 958, FM 832 and FM 989BR
Stoneville	13.6	ST 489BR and ST 4793R
Suregrow	5.4	SG 215 BG/RR
All-Tex	3.1	Atlas and Atlas RR
Phytogen	2.1	PHY 72 (Pima)

sells only its own brand name varieties, and seed companies are free to distribute any variety for general cultivation throughout the cotton belt. A system of self-accountability dominates the seed market, and companies are aware of tough competition among seed breeders. Healthy competition among seed companies ensures that only better performing varieties are promoted among farmers for general cultivation. There is no formal variety approval process, and if a variety has been released by a company, farmers are free to plant it on as much area as they want. However, extension agents and variety performance data suggest planting certain varieties in any given area.

• Top Ten Cotton Producing Countries

Ten countries planted 77% of the world's total area of cotton in 2003/04. The table (next page), shows that only six countries are among the 10 highest yielding countries in the world.

China (Mainland) is expected to produce one-fourth of world production in 2003/04, followed by the USA sharing almost 19% of world production. The top 10 countries are expected to produce 85% of world production; 50 other countries will produce only 15% of world production in 2003/04. Average yield have significantly improved in Brazil, China (Mainland) and Turkey in the last few years, while they have significantly fallen in Uzbekistan.

The world yield in 2003/04 is expected to be 616 kg/ha, 22 kilograms less than last year. The world average yield did not increase during 1990s, then rose to 642 kg/ha in 2001/02. Poor weather conditions are related to lower yields in the 2002/03 and 2003/04. The ICAC forecasts that the world yield will recover to the level of 2001/02 in 2004/05.

It is estimated by the ICAC that 6.7 million tons cotton will be traded in the world in 2003/04. The top 10 cotton growing countries will share 67% of world exports in 2003/04. Net exporting countries from the 10 will be Australia, Brazil, Greece, Syria, the USA and Uzbekistan. The USA is the largest exporter of cotton in the world, and will share about 38% of raw cotton exports in 2003/04.

Cotton is grown on at least 5,000 hectares in about 60 countries in the world. India always has the largest area. ICAC estimates for 2003/04 indicate that cotton was planted on 8.4 million hectares in India, which is about 26% of the world total area. Although in the last 10 years the USA has been the second largest cotton producing country by area, 2003/04 was the first year that cotton was planted on more area in China (Mainland) than in the USA. Pakistan, which has occupied the fourth position since 1988/89, saw a steady increase in cotton area to over three million hectares. An increase in yields of greater than 60% during the 1980s

World Cotton Production 2003/04					
Country	Area 000 ha	Production		Yield Kg/ha	Exports 000 tons
		000 tons	% of World		
Australia	180	286	1.4	1,587	348
Brazil	950	1,032	5.1	1,086	280
China (Mainland)	5,000	5,000	24.8	1,000	50
India	8,390	2,750	13.7	328	9
Greece	368	370	1.8	1,007	263
Pakistan	3,037	1,700	8.5	560	50
Syria	203	272	1.4	1,338	186
Turkey	725	925	4.6	1,276	35
USA	4,897	3,810	18.9	778	2577
Uzbekistan	1,393	940	4.7	675	687
Total	25,143	17,085	84.9	680	4,485
World	32,688	20,130	100	616	6,711

encouraged farmers in Pakistan to bring more area to cotton production. Brazil planted over three million hectares to cotton for four years from 1982/83. Brazilian cotton area started going down from 1986/87 to the lowest level of 694,000 hectares in 1998/99. Low yields in the north and northeast, high costs of insect control and government policies affected cotton area in Brazil. A shift in cotton production to the central part of Brazil, with fully mechanized conditions and high yield, is expected to recover some but not all of this area. Cotton area has significantly fallen in the last 10 years in Uzbekistan because of a combination of problems, including input supply and maintenance of farm equipment. In 2003/04, Australia is expected to plant cotton on almost half of its normal area due to a severe shortage of rainwater used in irrigation.

A DIALOG Search of Agricola and CAB Abstracts Databases

The key words used in the search are **cotton** and **strenght**, and the period covered is 1997 to date.

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Ephrata Senior High School, Ephrata, PA, USA.
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 Department of Botany and Microbiology, Auburn University, Auburn, AL 36849-5407, USA.
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Tao Ling Hu, Liu Wen Sheng, Feng Guo Lin, Chen De Hua, Wu Yun Kang, Ruan Xi Gen and Deng Jia Pei

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Subfile: IND; OTHER US (NOT EXP STN, EXT, USDA; SINCE 12/76)

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Zhang Xiang Qiong, Zhang Dong Ming, Zhou HongJun and Zhang Chao

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Li Shou Cheng and Jiang XianYan

Agricultural College, Sichuan Agricultural University, Ya'an, Sichuan Province, China.

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Hsieh You Lo

University of California, Davis, California, USA.

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INTERNATIONAL COTTON ADVISORY COMMITTEE

The International Cotton Advisory Committee is an association of governments having an interest in the production, export, import and consumption of cotton. It is an organization designed to promote cooperation in the solution of cotton problems, particularly those of international scope and significance.

The functions of the International Cotton Advisory Committee, as defined in the Rules and Regulations are

- To observe and keep in close touch with developments affecting the world cotton situation
- To collect and disseminate complete, authentic and timely statistics on world cotton production, trade, consumption, stocks and prices
- To suggest, as and when advisable, to the governments represented, any measures the Advisory Committee considers suitable and practicable for the furtherance of international collaboration directed towards developing and maintaining a sound world cotton economy
- To be the forum for international discussions on matters related to cotton prices

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