REGROWTH OF AUSTRALIAN COTTON VARIETIES AFTER SIMULATED DAMAGE BY HAIL

By

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Abstract

Hail simulation experiments were carried at the Australian Cotton Research Institute, Narrabri, Australia during the 1991/92 and 1992/93 cotton seasons with the aim of identifying differences in plant development and yield responses in cotton cultivars which may contribute to increased recovery from hail damage after damage to the canopy by hail. Two of the predominant commercial cultivars of cotton, Deltapine 90 and Siokra 1-4, were subjected to simulated hail damage at four stages of crop growth. Plant height, leaf area, fruit development, lint yield responses, time to maturity (60% open bolls) and changes in lint quality were monitored. Vegetative regrowth of the canopy after simulated damage followed similar patterns to the undamaged cotton within each season for each variety. Siokra 1-4 was found to grow more rapidly initially (ie. greater plant height and leaf area) than Deltapine 90. Vegetative and fruit development peaked in Siokra 1-4 earlier whilst Deltapine 90 continued to grow and reached a greater maximum height and leaf area. Following simulated damage, there was a delay of up to 14 days before regrowth occurred. Development was delayed for a period of 158 and 327 Growing Day Degrees after V3 and V5 stage damage respectively. Vegetative growth following this delay was increased over growth in undamaged cotton. Vegetative mass and peak square numbers were greater for cotton damaged in the vegetative stages than for undamaged cotton. No measurable vegetative recovery occurred following simulated damage in the reproductive stages.

Lint yield was reduced overall by hail damage but compensatory growth allowed for some degree of yield recovery depending on the growth stage at the time of damage. Maximum recovery was achieved when damage occurred in the vegetative growth stages and sufficient heat units remained in the growing season to allow maturity of late set fruit. Damage in the V3 growth stage did not consistently produce a reduction in yield, lint yield was increased by 5.4% over that of undamaged cotton in 1991/92 and decreased by 6.5% in 1992/93. Compensatory growth was reduced following V5 growth stage with lint yield reduced on average by 32%.

Recovery following damage in the reproductive stages was reduced due to the mature growth stage of the crop and insufficient heat units for maturation of regrowth. Yield losses averaged 65% following R8 stage simulated damage and 55% following R12+ stage damage. The yield recovery of the two cotton varieties was similar.

Simulated hail damage acted to delay crop maturity. Damage in the vegetative stages where crop compensatory growth was greatest produced the greatest delays in crop maturity V3 stage damage induced a 63-143 GDD (6-13 day) delay in crop development. V5 stage damage resulted in an increased delay in development with maturity delayed by 161-243 GDD or 15-23 days. Reproductive stage damage simulation had less effect on crop maturity with R8 stage damage delaying maturity by only 8-63 GDD (1-6 days). R12+ stage damage simulation had no effect on maturity in 1991/92 and advanced maturity by 45 GDD or 4 days in 1992/93 compared to undamaged cotton.

Fibre micronaire was reduced by simulated hail damage in the vegetative stages where crop maturity delays were greatest. No differences in lint quality between the cultivars were observed in terms of changes in fibre length, strength or micronaire following damage.

These experiments provide some evidence that loss assessment procedures may overestimate or underestimate yield losses. With optimum weather conditions following damage in the vegetative stages, compensatory growth saw yield losses reduced compared to the yield losses assessed at the time of damage. Regrowth following reproductive stage damage did not contribute to lint yield and losses were underestimated by the assessment procedures. Weather conditions after damage, season length, crop management and disease susceptibility have been identified as factors contributing to the degree of yield recovery achieved following hail damage.

Acknowledgements

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Certificate of Originality

The text of this thesis contains no material which has been accepted as part of the requirements for any other degree or diploma in this or any other University or any material previously published or written unless due reference to this work is made.

Signed: [redacted]

Karyl-Lee West

Chapter 1

General Introduction

Australian cotton production areas are prone to significant damage by hail storms. Losses due to hail occur at any time throughout the growing season. However, there is a higher frequency of storms and damage in spring which coincides with the crop establishment and vegetative growth period of cotton.

Crop insurance is available but is not a viable option for all growers. Insurance payouts for insured growers do not cover all costs incurred in a hail strike. Insurance claims totalling up to $13.6 million have been made by insurance companies in any one year for crop losses incurred due to hail damage (Table 1.1). The total loss to the Australian cotton industry is much higher, if you take into account uninsured crops, costs not covered by insurance, the original potential yield of the damaged crops and the cotton prices of the day.

Table 1.1: Australian Cotton Industry Hail Claims[1]

Cotton Season	Number of Storms	Number of Losses	Total Claims
1986/87	15	72	$ 1,894,124
1987/88	27	203	$ 7,756,419
1988/89	16	48	$ 2,829,664
1989/90	32	225	$13,617,519
1990/91	13	53	$ 1,538,045
1991/92	35	163	$ 9,126,447
1992/93	20	98	$ 3,619,081
1993/94	20	53	$ 1,129,729

[1] Source: Minet Agricultural Insurance Brokers Pty Ltd., North Sydney, Australia (1994).

The use of varieties which recover rapidly from hail damage may assist in reducing losses from hail damage. Prior to 1984, the predominant cotton varieties (*Gossypium hirsutum* L. cv Deltapine lines) grown in Australia were varieties bred in the United States. In 1984, the first major Australian bred varieties were released. These varieties were high yielding and well adapted to Australian cotton production areas and quickly became the predominant varieties planted. However, Deltapine 90 continues to be grown in significant areas representing approximately 20% of cotton production. The Australian bred cultivars are of different parentage and display different growth and fruiting patterns to the Deltapine lines (Gilbert, 1985; Thomson, 1986; Wells and Milroy, 1994). Following hail damage, field observations were made which suggest that there are differences between the Australian bred varieties and the Deltapine lines in their ability to regrow after damage (Cotton Research and Development Corporation, 1990, unpublished). The ability to replace lost vegetative material and initiate fruit rapidly may confer a more rapid or increased recovery from hail damage and assist in reducing losses due to hail damage.

Assessment of hail damage losses is made using the U. S. A. National Crop Insurance Service (N. C. I. S.) assessment procedures. These procedures were developed in the United States and are based on Acala type lines of which the Deltapine lines are representative. These procedures are applied to losses incurred by all varietal types and in all production areas.

Research into the effect of hail damage on cotton has not previously been carried out in Australia. This work was initiated to investigate the response of Australian bred varieties to hail damage. The aim of these experiments was to identify differences in regrowth which may contribute to recovery from simulated hail damage by comparing the growth and fruiting patterns and yield of the current Australian standard variety, Siokra 1-4 and the Deltapine cultivar. Damage was inflicted at several developmental stages and regrowth, yield and quality parameters measured. The application of the current loss procedures to assess loss for the range of Australian bred varieties now grown is also examined briefly.

Chapter 2

Review of Literature

Cotton (*Gossypium hirsutum* L.) and its Commercial Cultivation including a Discussion of the Effects of Hail Damage on Agricultural Crops with Specific Reference to Cotton.

2.1: Cotton Production Statistics

Cotton is arguably the world's most important vegetable fibre crop. It is cultivated in tropical and sub-tropical areas which provide a long warm growing season required by cotton.

World cotton production currently stands at an estimated 16.6 million tonnes. The world's major producers of cotton are China, U. S. A., the former U. S. S. R. particularly Uzbekistan, India and Pakistan. Production in Australia has expanded dramatically during the last 10 - 15 years and in 1993; Australia was the world's tenth largest producer of cotton lint and consistently produces some of the world's highest yields (Table 2.1.1).

Australia exports an average of 90% of the cotton lint it produces. Other major exporters are Uzbekistan, United States of America, West Africa, India, Pakistan and China (I. C. A. C., 1994).

Cotton cultivation is carried out under both dry land and irrigated farming systems ranging from large scale, highly mechanised production systems with high levels of inputs of fertilisers and pesticides in the United States and Australia, to small scale farming systems in China and parts of Africa where the entire crop is grown and harvested by hand (Figure 2.1.1).

Table 2.1.1: World Cotton Production Figures 1993[1]

	Total Area 1000s Ha	Avg. Yield Kg/Ha	Production 1000s metric tons
Nth America			
Cuba	4	269	1
Dom.Rep.	3	667	2
Mexico	29	754	22
United Sates	5390	749	4038
Sub-total	5441	747	4065
Central & South America			
Argentina	500	445	223
Bolivia	25	521	13
Brazil	1307	393	514
Colombia	118	566	67
Ecuador	20	418	8
El Salvador	5	810	4
Guatemala	15	1029	15
Nicaragua	2	662	1
Paraguay	480	475	228
Peru	49	625	31
Venezuela	40	469	19
Sub-total	2562	575.1	1122
Europe			
Bulgaria	10	430	4
Greece	350	743	260
Spain	32	937	30
Former Yugoslavia	1	240	
Sub-total	393	588	294
Central Asia (C.I.S.)			
Azerbaijan	223	561	125
Kazakhstan	110	636	70
Kirghizstan	20	700	14
Tadzhikistan	274	672	184
Turkmenia	578	761	440
Uzbekistan	1686	771	1300
Sub-total 1/	2891	738	2133
Asia			
China (Mainland)	5125	810	4150
Australia	232	1408	327
Indonesia	19	165	3
Korea, D.R.	8	377	3
Philippines	24	426	10
Thailand	40	467	19
Vietnam	18	129	2
Sub-total	5467	540	4514

	Total Area 1000s Ha	Avg. Yield Kg/Ha	Production 1000s metric tons
North Africa			
Egypt	371	906	336
Morocco	1	600	
Sudan	135	573	77
Tunisia	2	750	2
Sub-total	508	817	415
West Africa			
Benin	145	469	68
Burkina Faso	160	400	64
Cameroon	100	500	50
Cent.Afr.Rep.	30	267	8
Chad	170	235	40
Cote D'Ivoire	205	512	105
Madagascar	19	470	9
Mali	205	537	110
Niger	5	227	1
Senegal	40	500	20
Togo	80	437	35
Sub-total	1174	440	517
South East Africa			
Angola	10	382	4
Burundi	9	391	3
Ethiopia	41	369	15
Ghana	40	392	16
Kenya	62	112	7
Mozambique	86	146	13
Nigeria	430	128	55
South Africa	57	373	21
Tanzania	344	162	56
Uganda	121	56	7
Zaire	6	143	1
Zambia	101	170	17
Zimbabwe	260	290	75
Sub-total	1635	186	304
Indian Sub-continent			
Afghanistan	60	360	22
Bangladesh	35	857	30
India	7700	287	2210
Myanmar	160	144	23
Pakistan	2941	665	1955
Sub-total	10900	389	4241
Saudi continent			
Iran	205	556	114
Iraq	4	427	2
Israel	16	1688	27
Syria	195	1037	202
Turkey	555	925	514
Sub-total	997	869	867
World Total 1/	**31971**	**578**	**18473**

1/ Subtotals and Totals include countries not shown

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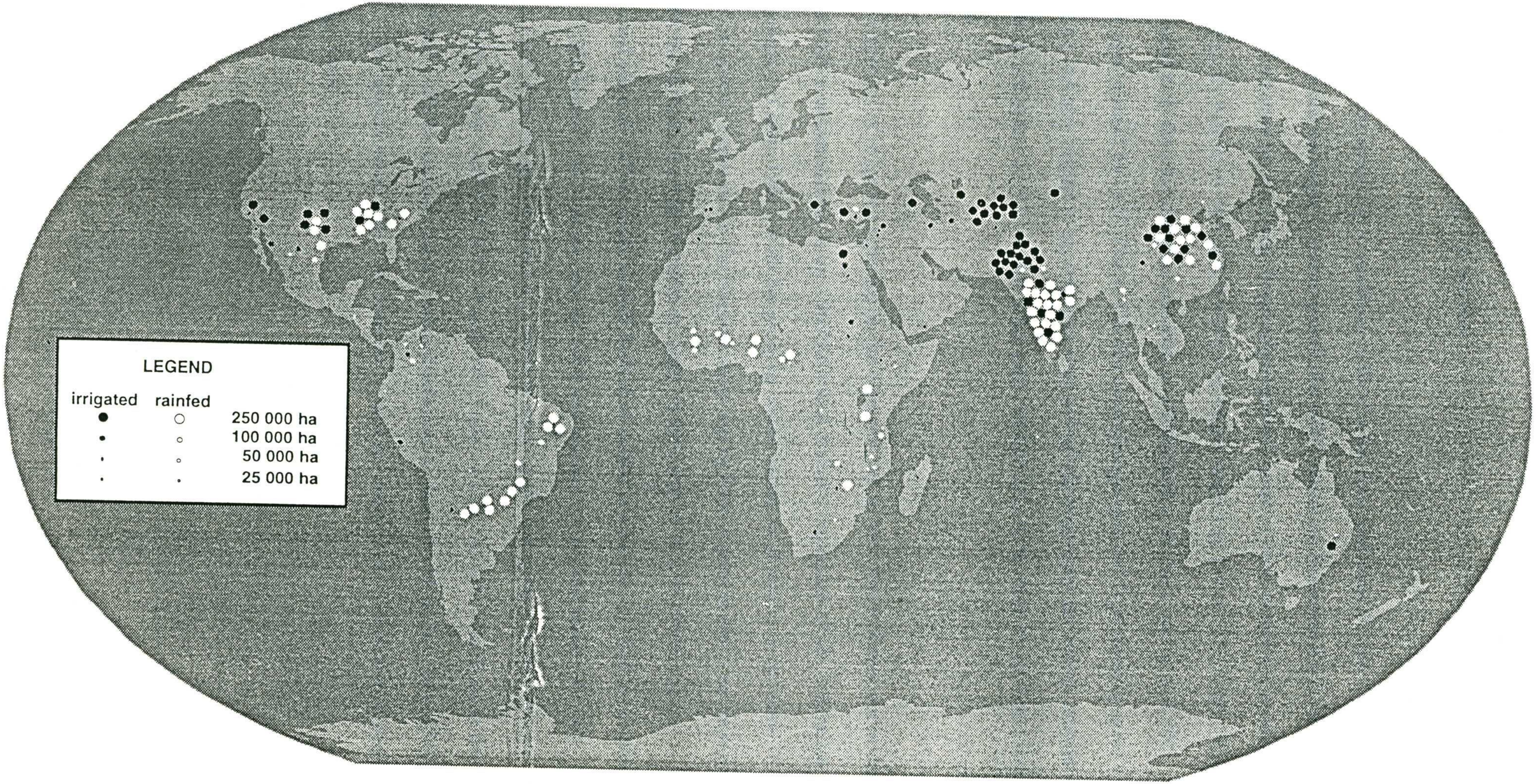
[1] Source: "Cotton: World Statistics" Bulletin of International Cotton Advisory Committee, October, 1993.

Figure 2.1.1: World Areas of Irrigated and Rainfed Cotton
Source: Hearn, 1995



Trends in Australian Cotton Production

Cotton was first introduced to Australia in 1788 with the first settlement (Cribb, 1986). The cotton industry did not begin to develop until the 1870's when the American Civil War created a world shortage of cotton. Production reached a peak of 3640 tonnes but production declined rapidly thereafter. When boll weevil problems developed in the U. S. in the 1920s further attempts at dry land cotton production in Queensland were made and up to 8,000 hectares were planted by 1923. Due to inferior crop management and high shipping costs to Europe, the industry battled to expand further and even with a government bounty introduced to Central Queensland in 1927, cotton areas only reached 20,230 hectares by 1933 and then declined.

The development of irrigation schemes on the Namoi River in New South Wales and in the Lochyer Valley in Queensland in the 1960's allowed dramatic expansion of the Australian cotton industry (Cribb, 1986). With the growing cotton expertise of two U. S. growers, production quickly expanded in the Namoi Valley and by 1968 Australia was a net exporter of cotton lint. Irrigation schemes based on dams on the northern N.S.W. rivers and in Queensland allowed further expansion of Australian cotton production. In 1964 production was at 11,300 bales (2,543 tonnes) and by 1984 had reached 1.1 million bales (247,500 tonnes). Production reached a peak of 2.2 million bales or 495,000 tonnes in the 1991/92 season of which approximately 90% is exported (Figure 2.1.2). Drought conditions in the 1992/93 and 1993/94 seasons caused cotton production to drop to 1.38 million bales (310,500 tonnes). Now approximately 260,000 hectares of land are under cotton production annually (Dowling, 1994).

The major production areas in Queensland are at St. George, Theodore, Biloela, the Emerald irrigation area and on the Darling Downs. In New South Wales, production is centred along the northern river valleys of the MacIntyre, Gwydir, Namoi and Macquarie rivers, on the Darling River at Bourke with production now expanding south to the Menindee Lakes, Hillston and Hay areas (Figure 2.1.3 and Appendix 2.1).

Figure 2.1.2: **Cotton Production in Australia, 1978-1994**

(1 Bale of Lint Cotton = 225 kg)

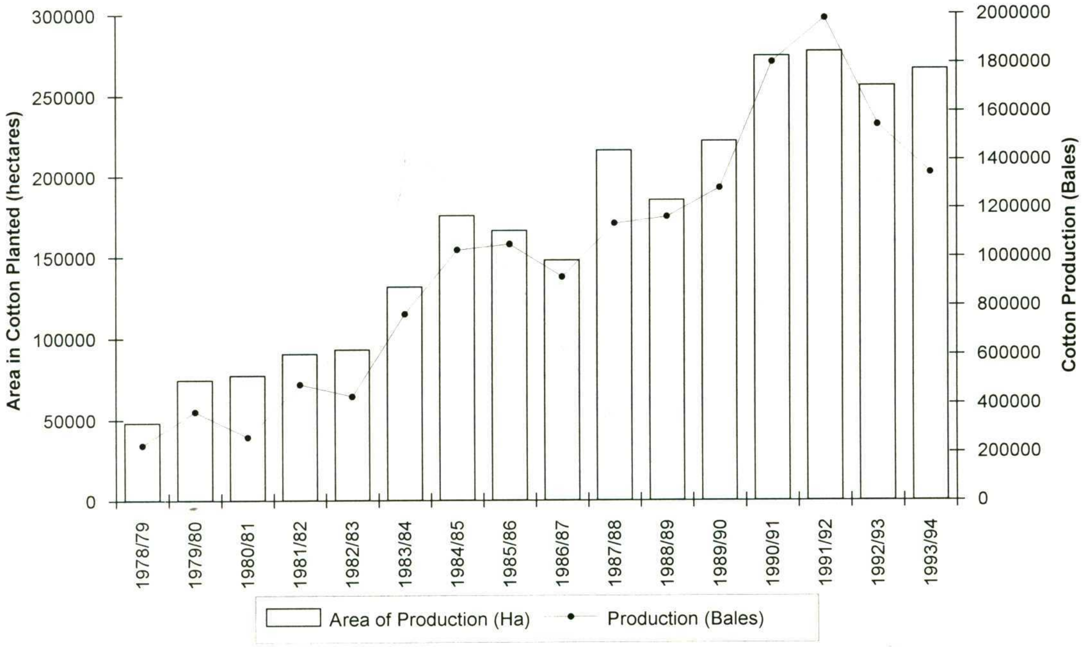
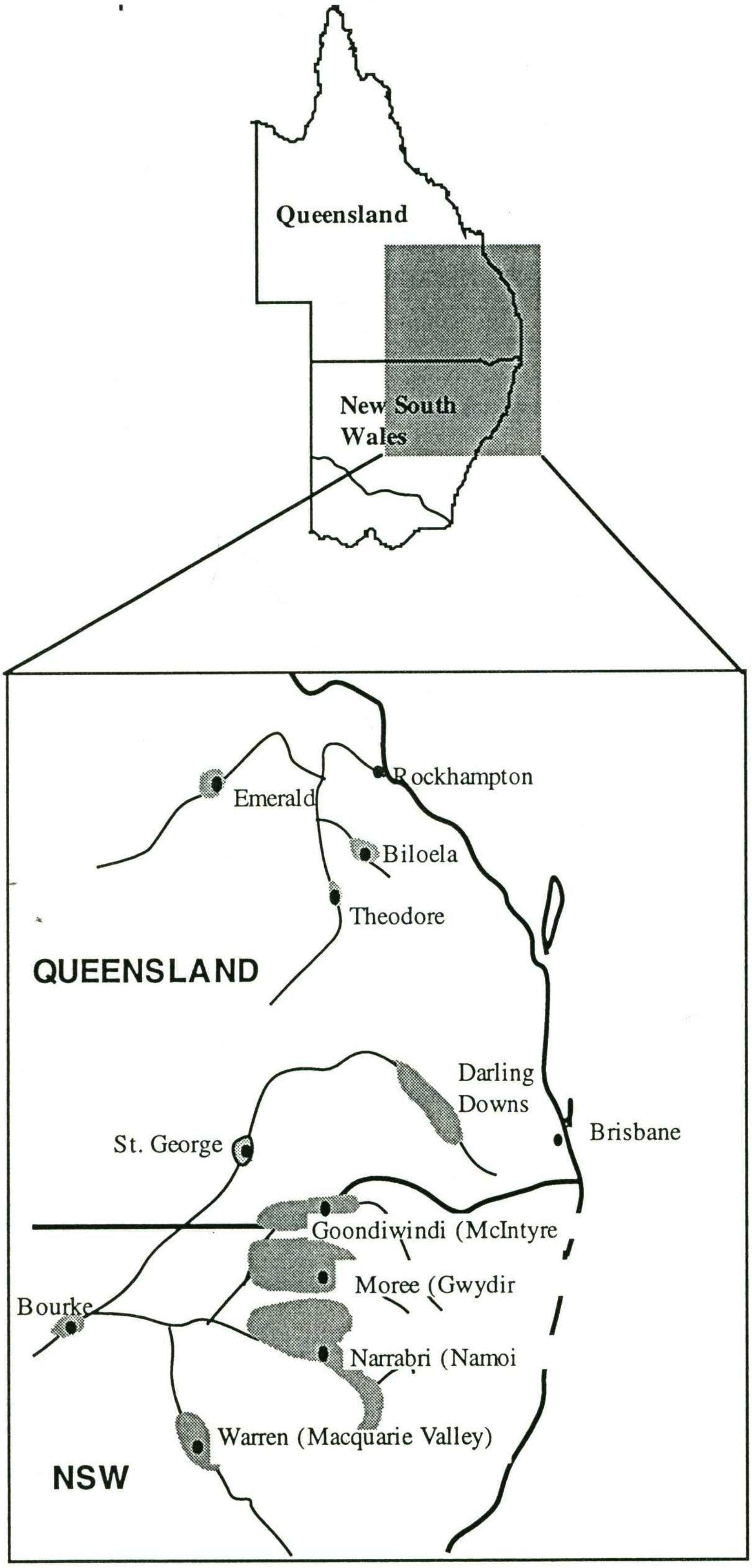


Figure 2.1.3: Cotton Production Areas of Australia
Source: Australian Cotton Research Institute



2.2: Cotton as a Cultivated Plant

Commercially cultivated cotton belongs to the genus *Gossypium*, a genus of the Malvaceae family. It is a genus of diverse morphology containing over fifty species. Only four of the species are cultivated in commercial production, two Asian species (*G. arboreum* and *G. herbaceum*) and two American cultivated species (*G. hirsutum* and *G. barbadense*) (Thomson, 1975).

The commercial species bear long convoluted fibre or lint on their seed which can easily be removed and spun into commercial cotton. This is compared to the "wild species" which bear short rod-like fibres adhering strongly to the seed coat and cannot be spun, an exception is a wild Hawaiian species, *G. tomentosum* (Thomson, 1975).

The wild species of *Gossypium* are perennial xerophytic shrubs or small trees which grow in arid regions of the tropics and sub-tropics. The most common habitat is in desert fringes, in dry river beds, and for some species which are sufficiently drought-resistant, in arid, rocky hillsides and plains, although each species has a limited distribution (Purseglove, 1974).

Early descriptions of the genus were based on morphological characteristics such as seed coat covering, inflorescence type, shape of calyx and bracteole form of herbarium specimens (Watt, 1907 cited by Berger, 1969). Cytological studies by Skovsted (1937) and Webber (1939) showed that all the "wild" lintless species were diploid with 2n=26 chromosomes as were the cultivated Asiatic species while the cultivated American species were polyploid with 2n=52 chromosomes. Skovsted (1937) and Webber (1939) concluded that the species are naturally differentiated cytogenetically into six genomic groups which conform with the historic geographical separation of the species.

Hutchinson *et al.* (1947) in an extensive study of the morphology, cytology and geographical separation of the species classified the species into eight sections. Based on lack of homology in crosses between some species, they divided the American wild species into three sections. This study covered the twenty species then identified and is the generally accepted classification (Table 2.2.1). Recent studies by Hutchinson (1954), Saunders (1961), Fryxell (1969) and Stewart (1988) include newly identified species or minor movement of species between sections. Stewart, (1994) and Craven *et al.*, (1994) currently acknowledge 50 species of Gossypium including 17 which are endemic to Australia, many of which have only been identified in the last decade.

All species of *Gossypium* have at least some seed hairs, but the length and diameter of the seed hairs varies between species. In the wild species, the seed hairs adhere strongly to the seed surface and can be short and almost invisible to the naked eye or up to 10 - 12 mm.

The major difference between the "wild' and linted species is the quantity of cellulose laid down in the seed hair cell. The seed hair cell is initially thin walled, but as the seed matures cellulose is laid down within the cell cuticle in a spiral formation. At maturity, in the wild species, the lumen of the cell is almost filled so that the mature seed hair is long, tapered, circular in cross section and filled with cellulose except for a small central lumen left by the cytoplasm. In linted species, less cellulose is deposited and a considerable lumen remains in the cell at maturity. When the capsule opens and the lint hair dries, the lumen collapses and the hair forms a ribbon shape. The spiral deposition of cellulose causes the lint hair to form convolutions as the lumen collapses and this characteristic enables such lint hair to be spun.

The reduction in cellulose deposition which changes a seed hair from a simple hair to a lint hair is considered a genetically simple change. Hutchinson *et al.* (1947) concluded from cytological studies that the most ancient cultivated cotton is *G. herbaceum* (Section Herbacea). It is the only cultivated species which occurs naturally in the wild, ie. *G. herbaceum* race *africanum*, as found in southern Africa, and is considered the most likely species in which the mutation to lint occurred (Hutchinson, 1954). The linted species was then transported by man to Arabia, Central Asia and South East Asia for use in cultivation where various races developed.

Further information of the linted species of the *Gossypium* genus is presented in Appendix 2.2.

Table 2.2.1: The Classification of *Gossypium*[1]

	A: WILD LINTLESS SPECIES					
	Section	**Description**	**Genome**		**Examples of Species**	**Races**
I	Sturtiana	Wild Australian Species	C	2n=26	G. sturtii, G. robinsonii, G. australe	
II	Erioxyla	Wild American species centring in Southern California and on the Pacific coast of Mexico	D	2n=26	G. aridum, G. armourianum	
III	Klotzschiana	Wild American species centring in Western Mexico, the Galapagos Islands and Peru.	D	2n=26	G. klotzschianum var klotzschianum G. raimondii	
IV	Thurberana	Wild American species centring in Arizona and Mexico.	D	2n=26	G. thurberi, G. gossypioides	
V	Anomala	Wild species centring on Africa	B	2n=26	G. anomalum	
VI	Stocksiana	Wild species centring on Arabian peninsula	E	2n=26		
	B: LINTED SPECIES					
VII	Herbacea	Asian cultivated species	A	2n=26	G. herbaceum	africanum acerifolium persicum kuljianum wightianum
					G. arboreum	indicum burmanicum cernuum sinense bengalense soudanense
VIII	Hirsuta	Polyploid cultivated species, *G. barbadense* and *G. hirsutum*, and wild species from Hawaiian islands *G. tomentosum* .	AD	2n=52	G.barbadense	brasiliense darwinii
					G. hirsutum	marie-galante punctatum latifolium
					G. tomentosum	

[1] Source: Adapted from Thomson (1975), Purseglove (1974), Berger (1969).

2.3: Cotton Morphology

The morphology of cotton has been reviewed by Berger (1969), Brown and Ware (1958), Hutchinson *et al.* (1947), Mauney (1985), Purseglove (1979) and Thomson (1975). This description of the morphology of cotton is based on these works.

The classical description of the genus *Gossypium* (Hutchinson *et al.*, 1947) describes the genus as follows:-

"Haploid chromosome number 13 or 26. Annual sub-shrubs, perennial shrubs or small trees. Branches terete or slightly angled, tomentose, hairy or glabrous, of two kinds, monopodial vegetative branches and sympodial fruiting branches, the latter sometimes reduced to jointed peduncles or flowering spurs. The whole plant irregularly dotted with black oil glands. Bracteoles 3, usually foliar and persistent, sometimes small, or minute, rarely caducous. Calyx cup-shaped, truncate, undulate or five pointed. Stamens ∞, the lower parts of the filaments united into a tube, the upper free, bearing unilocular anthers. Styles clavate or furrowed, rarely divided at the tip. Ovary 3-5 locular, ripening to a dry, brittle, loculicidally dehiscent capsule. Loculi with seeds indefinite (rarely 2 only). Seeds covered with one or two coats of long unicellular hairs, or in some wild species almost naked".

Hutchinson *et al.* (1947) divided the sections of the genus on the basis of cytogenetics and on morphology and a summary of the important diagnostic characters of the sections is presented in Table 2.3.1 in Appendix 2.3. The genus as a whole consists of annual sub-shrubs, perennial shrubs or small trees of variable morphology. Of course, the Hirsuta section provides most of the species which are in commercial production today, as *G. hirsutum* American Upland varieties have spread world wide and replaced the Old World or Asian species in most of the world's production areas and are therefore the most agriculturally important species. Hence, this description of the morphology of cotton concentrates on the morphology of the *G. hirsutum* American Upland types.

The general shape of a cotton plant is somewhat pyramidal or conical with variations due to differences in the length of the branches. The fully developed cotton plant has a prominent monopodial main stem with an indeterminate apex. Stem and branch length is determined by environmental and production conditions or to some extent are a characteristics of the species or variety, or of annual / perennial habit (Brown and Ware, 1958). The modern varieties, i.e. American Upland types, are perennial sub-shrubs with an annual growth habit and not true annuals. They have been selected to grow, produce fruit and mature within the frost free period in areas which experience frost.

During germination of the cotton seed, the radicle emerges and develops to form the primary root. The hypocotyl of the embryo emerges and elongates through an inverted "U" and carries the distinctive kidney-shaped cotyledons above the soil line (Figure 2.3.1). Slow seedling growth and intolerance to competition in the early stages of development are characteristics carried through from the ancient wild species from which the commercially grown cultivars were developed (Thomson, 1975).

The true leaves are arranged spirally (3/8 phyllotaxy) on the main axis and its vegetative branches (Figure 2.3.2). The first true leaves are not usually lobed and the characteristic lobed shape in not reached until leaves of about the 10th main stem node are produced (Berger, 1969). Most species and varieties have five lobes, but the actual shape can vary from almost entirely rounded to deeply dissected. The leaf blade is papery and thin in Upland types whereas the *G. barbadense* or Egyptian cottons have a thicker, more leathery leaf. The leaf may be glabrous or hairy; the degree of hairiness is a characteristic of the variety and species.

Figure 2.3.1: **Germination and Seedling Emergence**
Source: Oosterhuis (1990).

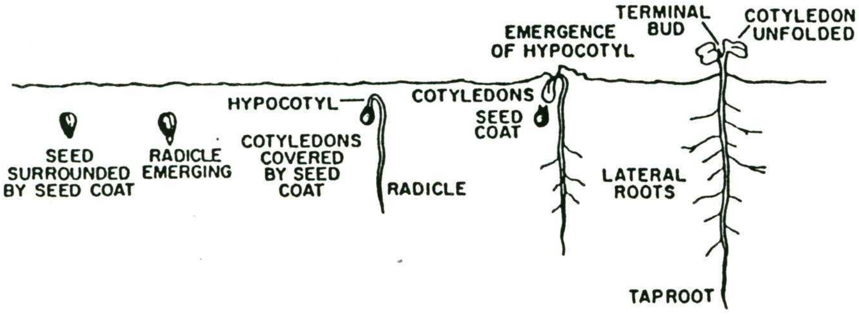
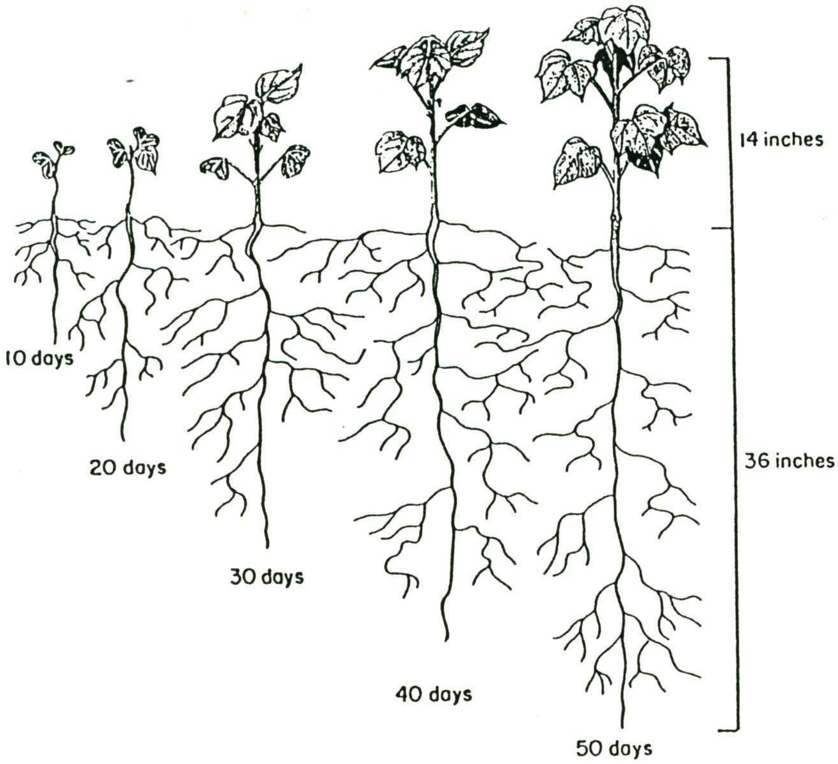


Figure 2.3.2: **Seedling Establishment Showing the Development of the True Leaves on the Main Stem.**
Source: Oosterhuis (1990).



Secondary branches develop from the main stem and are either vegetative or reproductive (Mauney, 1985). Vegetative branches are similar in structure to the main stem (i.e. monopodial) and normally arise from the main stem at lower nodes but are almost non-existent in large scale commercial production where the high plant population induces a less spreading habit unless the terminal bud is aborted due to insect, hail or other damage. Reproductive branches are sympodial in structure, the terminal bud produces a flower and the branch is carried on by growth from the axillary bud in the leaf axil giving the branch a zigzag appearance (Berger, 1969). Oosterhuis (1990) presents the structure of the cotton plant diagrammatically (Figures 2.3.3 and 2.3.4).

The first fruiting branch is usually produced at the 6-8 th node on the main stem. Fruiting branches then tend to be produced at each successive node after fruiting begins. Approximately 6-8 flower buds are produced on each fruiting branch with the longest fruiting branches being found in the mid section of the plant. A typical fruiting branch is illustrated in Figure 2.3.5. The rate at which flower buds appear along a fruiting branch and the rate at which the main stem nodes appear is a varietal characteristic giving a ratio constant over a range of environments (Hearn, 1969a). The rate of production of flower buds is affected by further vegetative branch growth and by the fruiting branches successively becoming inactive and ceasing to grow.

Cotton flower buds, commonly called squares, consist of three triangular bracts or bracteoles forming a pyramidal structure. The bracts initially envelope the inconspicuous cup-shaped calyx and actual flower bud.

Figure 2.3.3: **Structural Development of the Cotton Plant showing Main Stem, Vegetative (Monopodial) Branches and Fruiting (Sympodial) Branches.**
Source: Oosterhuis (1990).

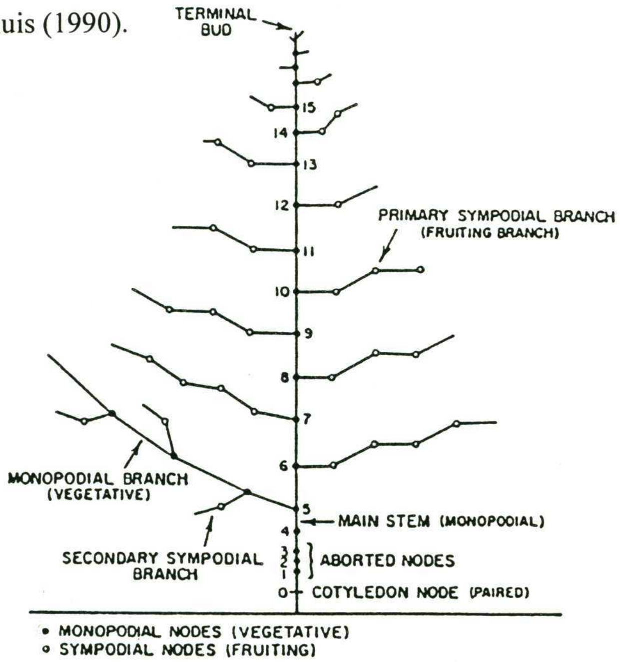


Figure 2.3.4: **Development of Main Leaves and Sympodial Leaves Along A Fruiting Branch**
Source: Oosterhuis (1990).

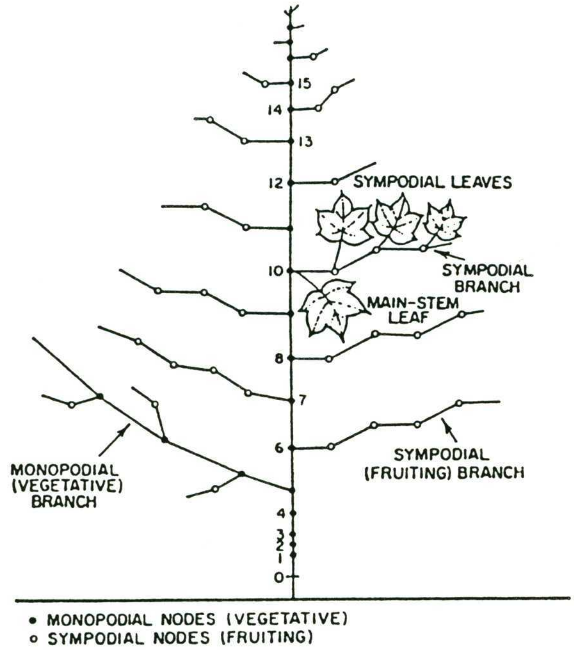
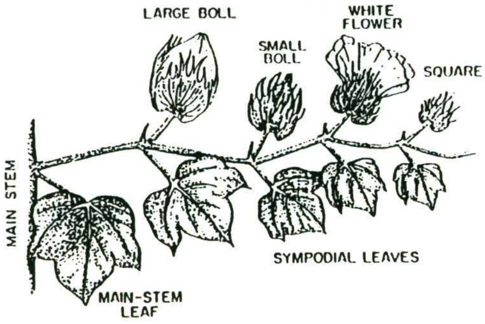


Figure 2.3.5: Cotton Fruiting Forms
Source: Oosterhuis (1990).



The flower is a typical Malvaceae type with five petals arranged in a whorl around a prominent staminal column with short-filament anthers. The colour of the corolla varies with species and variety, from white or ivory or light yellow in Upland types or deep yellow with a red spot at the base of the petals in *G. barbadense* types. The corolla changes colour before shedding through to purple-red or blue-red. The first flowers to open are low on the plant and near the main stem; the next are further out on the same fruiting branch. The order is spirally outward and upward. The interval between successive flowers in the spiral is approximately three days and between flowers on the same fruiting branch approximately 6 days (Berger, 1969).

The staminal column covers all the ovary and part of the style so that only the protruding stigma is noticeable. The ovary is 3-5 locular in *G. hirsutum* American Upland types or 3-4 locular in *G. arboreum, G. barbadense* and *G. herbaceum* (Thomson, 1975).

Cotton flowers are usually self-pollinated. The fruit capsule of cotton (i.e. cotton boll) commences growing 4-5 days after fertilisation with maximum size being attained in 15-18 days (Thomson, 1975). Bolls of Upland types are usually light green in colour, smooth with few oil glands compared to *G. barbadense* bolls which are darker and pitted with a large number of oil glands. Boll size and shape is a characteristic of the species and variety. Development continues internally for another 30 - 40 days before boll opening, depending on temperature. Internally, boll growth occurs through enlargement of the seeds (5-11 per locule) and the epidermal cells of the testa (seed coat). The epidermal cells produce two types of hair, namely short convoluted hair or fuzz which is firmly attached to the testa and the long convoluted hairs or lint. Although some species of cotton may not possess the short convoluted hair and hence have a naked seed, current commercially cultivated lines have such hairs. They are white in the case of the Upland types, green or brown in the case of Egyptian types. Final lint length is usually attained in about 20 days and thereafter secondary wall thickening of the fibre takes place by cellulose deposition until the mature boll splits open. At maturity, the boll splits along the lines of division of the carpel, the seed-cotton dries and fluffs out in separate locks corresponding to the number of locules in the ovary.

The number of bolls reaching maturity comprises only some 20-50% of the total number of fruiting forms initiated. The remainder are shed, mostly either as squares at a very early (pinhead) stage, or as small bolls in the first few days following anthesis (Guinn, 1982; Thomson, 1975).

The increasing number of fruit gradually retards vegetative growth and the main stem and branches eventually cease to extend in length. As the plant reaches its capacity boll load terminal growth stops and the crop matures the boll load set.

The main stem of the cotton plant is continuous with the main root i.e. the taproot. Laterals arise from the main root and spread more or less horizontally and can penetrate the soil to the depth of the taproot, forming sub-branches as they develop. The cotton plant usually has a comparatively deep root system. The zone of soil that is penetrated by the root system is dependent on soil moisture, soil structure and the size or age of the plant. Brown and Ware (1958) in reviewing studies by Balls (1919), Hubbard (1933) and Cheng (1950), shows root growth in Upland cottons reaching a depth of 2.1 metres in mature plants in irrigated alluvial soils; Egyptian cotton in similar conditions had root development to similar depths. They suggested that perennial cottons have more extensive root systems than the 'annual' cottons.

2.4: Physiology of the Cotton Plant

As an indeterminate plant, there is no morphological limit to the development of the cotton plant and no limit to the number of fruiting structures. The indeterminate main stem produces a new node every 2-4 days. Flower buds are produced on the sympodial fruiting branches which develop from each of the main stem nodes beginning with the 5-8 node, depending on environmental conditions. Hence, as the main stem develops, an ever increasing number of flower buds are initiated which have the potential of contributing to lint yield. In practise, development is limited by environmental and physiological factors. Temperature, water and nutrient levels act to limit or restrict physiological processes and hence affect germination, growth of plant parts and dry matter production, fruit production and maturation.

Carbohydrate and nitrogen demand of the developing fruit increases exponentially as the plant develops, however, the production or uptake of carbohydrate and nitrogen supplies is limited (Hearn, 1979). Competition for nitrogen and carbohydrates develops between the various growing organs of the plant. The plant reduces the rate of morphological development, flowering and boll set and fruit that are not set as bolls are shed. Square production stops and the plant is termed as having reached "cut out" when the maximum boll load that is attainable under the given conditions is reached (Hearn, 1979). The plant may restart and produce a second fruiting phase as bolls mature and no longer act as sinks for assimilates. This enables the cotton plant to compensate for periods of limited supply of plant requirements. The internal competition between assimilate sinks affects the number of bolls set and influences the rate of square production, and provides a strong feed-back mechanism for control of development (Hearn, 1979).

Reviews of the developmental physiology of cotton include the work of Brown and Ware (1958), Guinn (1986), Hearn and Constable (1984) and Oosterhuis (1990). These papers provide the basis for the following discussion.

Water Relations

Hearn (1979) describes the influence of water supply on crop development in different environments. For example, cotton in southern Arabia is grown on water stored in the soil profile from winter flood water with no rainfall during the growing season. The root system explores the soil to the full depth of soil moisture. The upper part of the plant develops at a rate independent of available water until approximately two-thirds of the available water has been used and then abruptly ceases growth and the remaining water is left to mature the bolls already set. A fuller profile of water at the start of the season results in an extended growth and fruiting phase and higher yield.

The development of rain-grown and irrigated cotton is similar to this model. Rain-grown cotton experiences a series of drying cycles and hence a series of growth or fruiting phases. Hutchinson *et al.* (1958) found that leaf area and overall development of rain grown cotton crops of tropical areas continued without restriction until the onset of water deficit. Water supply determines the start and finish of the growing season and maximum yields were achieved by planting and matching the periods of peak water use by the crop to the periods of maximum available soil water. Under irrigation, the aim is to apply water to maintain the original fruiting phase (Hearn, 1972).

The xerophytic characteristics of the cotton plant allows it to adjust to water stress. Water is absorbed by the root hairs near the root tip (Brown and Ware, 1958). The root system penetrates a large mass of soil when conditions are favourable, and so under water deficit situations the plant is able to draw water from deep in the soil profile. Cotton grown on shallow soils or where impervious layers in the profile prevent the formation of a deep root system shows less tolerance to drought conditions. The ability to draw water from depth is also affected by the destruction of roots such as by root pruning during cultivation, where the absorption surface is reduced. The rate of water absorption is not only affected by available water but is also affected by temperature and aeration of the roots (Brown and Ware, 1958).

The rate of transpiration increases as leaf temperature increases (as long as water is available to replace that lost) and hence evaporative cooling during transpiration becomes important in assisting in lowering leaf temperature (Brown and Ware, 1958). As water deficit expresses itself as a cessation of cell expansion, plant height increases ceases as does leaf expansion, node production and square production.

Cotton, as with other xerophytes, also responds to gradual water stress by osmotic adjustment (Hearn and Constable, 1984). Osmotic potential and turgor pressure are two of the components of leaf water potential (LWP). Leaf growth and stomatal closure both respond to turgor pressure but have different deficit thresholds. Stomatal closure is found to occur at lower leaf water potentials than that at which leaf growth stops, and by osmotic adjustment the point when leaves stop growing and stomata closure occurs is deferred (Hearn, 1979). Net photosynthesis is found to decline at similar LWP to that at which osmotic adjustment occurs (Hearn and Constable, 1984). Generally there is a linear decline in leaf growth with LWP decreasing from -1.2 to -2.4 MPa and a linear decline in photosynthesis below -2.0 MPa LWP.

Grimes and Yamada (1982) cited by Hearn and Constable (1984), found that boll growth was not affected until leaf water potential reached -2.7 to -2.8 MPa. These deficits were even lower than those for cessation of leaf expansion and photosynthesis decline. Hence, although stomatal closure occurs at a given water deficit, the cotton plant is able to remain metabollically active at relatively higher water deficits.

Since vegetative growth, fruit growth and photosynthesis have different water deficit thresholds in cotton. Vegetative growth is maximised and carrying capacity and boll set is reduced where water stress is minimal, i.e. where leaf water potential or deficit (LWP) is less than -1.5 Mpa, such as in well-watered but not waterlogged cotton or in cloudy weather (Hearn and Constable, 1984). This situation, if combined with high nitrogen, can lead to rank growth and associated insect control problems, boll rot and delayed maturity. The dense canopy shades lower bolls and causes shedding. Without the boll load building up, leaf and square production are the only sinks for assimilates and vegetative growth is maintained. This is reminiscent of the wild species of cotton, where with plentiful water, vegetative growth is maximised and shedding of young fruit occurs and fruit setting is deferred until dry weather (Hearn and Constable, 1984).

Mild stress (LWP -1.5 to -2.0 MPa) is the most desirable situation in commercial production as it maximises boll set. Vegetative growth is checked but boll growth and photosynthesis are unaffected. LWP below -2.0 Mpa act to reduce squaring and finally to stop squaring and stop boll set (Hearn and Constable, 1984).

Temperature Relations

Although originally a tropical perennial plant, cotton has been adapted through selection pressure to grow in a range of climates with a large proportion of commercial production being in temperate areas where the crop is essentially grown as an annual. Cotton grows best in relatively hot dry regions. Temperature imposes major restrictions on cotton growth, determining planting dates, the rates of germination and development, fibre lint quality and the length of the growing season and hence yield potential.

The cotton plant's lack of tolerance of low temperatures means that germination and early plant growth are affected markedly by temperature. Constable (1976) found that all growth and development was stopped by temperatures of 11.4 ^{0}C and that a temperature minimum of 14 ^{0}C was required for germination. Early studies by Arndt (1937), Ludwig (1932) as cited by Christiansen and Rowland (1986) established minimum temperatures for germination with temperatures below 15 ^{0}C being deleterious to germinating seed.

In commercial cultivation, with adequate soil moisture and aeration, the rate of germination and emergence is a function of temperature (Wanjura *et al.*, 1970). There is a strong relationship between percentage germination, and time to emergence (McQuigg and Calvert, 1966; Wanjura *et al.*, 1969), with the time to emergence decreasing with increased temperature up to a maximum at 32.2 ^{0}C. Time to emergence increases when soil temperatures at planting go above 37.8 ^{0}C (Wanjura and Buxton, 1972). The effect of soil temperature on the rate of seedling emergence is presented in Table 2.4.2. The rate of radicle elongation was decreased by high soil impedance and lower pH (Pearson *et al.*, 1970).

Table 2.4.1: Effect of Soil Temperature On Seedling Emergence[1]

Soil Minimum Temperature at 10 cm (^{0}C)	Seeds Emerging and Surviving (%)	Days to Complete Emergence
10	56	29
14	73	17
18	90	5

[1] Source: Constable (1988b)

As with germination, the growth and development of the cotton plant is temperature driven. Low temperatures impede growth, with temperatures below 12 ^{0}C causing chilling injury to seedlings (Christiansen and Rowland, 1986). Water uptake is disrupted as radicle cortical cells are destroyed by the low temperatures. Morphological and anatomical changes are induced by the damage and common symptoms of chilling injury during early growth is a reduced rate of growth, small size of first and second true leaves and abortion of the root terminal (Christiansen and Rowland, 1986).

Temperatures above 38 ^{0}C affect growth by decreasing water movement and photosynthesis, and also by decreasing boll set (Brown and Ware, 1958). Since high night temperatures usually follow high day temperatures, maintenance respiration increases further depleting carbohydrate supplies and hence yield potential is decreased. Maintenance respiration is doubled for each 10 ^{0}C rise in temperature (Hearn and Constable, 1984).

Meyer (1969) found markedly increased anther sterility with temperatures at flowering above 38 ^{0}C and the effect was increased with increased relative humidity. Hoffman and Rawlins (1970) emphasised the importance of relative humidity showing that constantly low (25%) relative humidity or constantly high (90%) relative humidity reduced yield by causing anthers to fail to dehisce and thus reducing boll set. Taha *et al.* (1981) in field trials found greatly reduced boll set and heat induced sterility for flowers produced during the hottest periods of the season, when long term average maximum temperatures were 43.1 ^{0}C and minimum of 29.0 ^{0}C.

Photosynthetic rates are affected by the temperature regimes under which a crop is grown (Downton and Slatyer, 1972). El-Sharkawy and Hesketh (1964) found that at high temperatures and water deficits photosynthesis rates were decreased. Cotton leaves may wilt at high temperatures but the stomata remained open and photosynthesis continued at lower rates up to temperatures of approximately 38 ^{0}C.

The optimum temperature for growth is approximately 32 ^{0}C (Hesketh and Low, 1968). There is a potential for a plant to produce a new node every 40 day degrees (2-4 days) in the temperature range of 20 - 35 ^{0}C (Hearn, 1969a). Temperatures in this range shorten the length of several developmental phases and indicates that development is temperature driven and not linearly related to chronological time.

Moraghan *et al.* (1968) found that low night temperatures or low temperatures during early growth produced a smaller leaf area in plants at squaring and increased the time to squaring. Growth was slower at low temperatures and so time from emergence to squaring was not constant. Constable (1976) found a delay of one week in planting decreased the planting to emergence phase by 0.9 days, the emergence to squaring phase by 2.2 days and the squaring to flowering phase by 0.4 days. These findings agreed with the work of Hesketh *et al.* (1968) who found that days from squaring to flowering and from flowering to boll opening were markedly affected by temperature and optimum temperatures for vegetative growth were regimes of 30/25 ^{0}C to 33/28 ^{0}C. Optimum temperatures for boll production were found to be lower at 27/22 ^{0}C to 30/25 ^{0}C. Mutsaers (1976) describes the negative exponential relationship between temperature and the length of the boll maturation period. The optimum temperature for boll development varied with the level of solar radiation available, with higher radiation levels lowering the optimum temperature for boll development (Hesketh and Low, 1968).

If the length of the different growth phases of cotton varies with temperature then morphological development cannot be defined in terms of chronological time. Thermal time provides a more accurate measurement and hence, the units generally used to describe the length of growth phases is the thermal time requirement for each phase, Growing Degree Days (GDD). Peng *et al.* (1989) documented the correlation of growth of cotton with growing day degrees. They observed that the high correlation ($r^2 = 0.90$) with GDD holds when temperature is the primary driving force but does not hold where water is limiting and overrides temperature as the major limiting factor.

Growing Degree Days are calculated by the following formula :-

$$\text{Growing Day Degrees} \quad = \quad \frac{(T_{max} + T_{min})}{2} \quad - \quad T_b$$

Where T_{max} and T_{min} are the daily maximum and minimum temperatures respectively and T_b is the base temperature.

McMahon and Low (1972) used GDD (T_b 10 ^{0}C) and long term climatic data to define areas of eastern Australia suitable for cotton production. Constable (1976) has since determined a base temperature of 12 ^{0}C to be more accurate as below this temperature no development occurs in cotton. If the daily minimum drops below 12 ^{0}C, a value of zero is used for the GDD.

The periods from emergence to first square and the development of each of the fruit have specific heat unit requirements. But, the indeterminate growth pattern of cotton means at any one time the crop is growing both vegetatively and reproductively by producing squares and bolls. The length of the flowering and boll maturation periods is determined by the rate of setting fruit which is influenced by temperature and also the internal nitrogen and carbohydrates balance, water relations and insect infestation (Hearn and Constable, 1984). It varies depending on the degree of vegetative development the crop attains and the number of fruit produced and hence, the overall thermal time requirement for a crop cannot be defined readily. GDD values have been determined for the various phases of development. Average total day degree requirements for phases of development are given in Table 2.4.1.

Minimum spring temperatures and overall frost free days determine the overall limits to cotton production in temperate areas (Brown and Ware, 1958). Brown and Ware (1958) state that the delineation of cotton growing areas in the U. S. adheres strongly to the 200 frost free day (FF days) climatic contours. Cardozier (1957) and Papadakis (1966) cited by Thomson (1975) state that cotton requires a minimum of 180 FF days for economic production.

In view of the temperature requirements for cotton growth (Constable, 1976; Hesketh *et al.*, 1968) and the relationship between lint yield and heat unit accumulation (Peng *et al.*, 1989; Mc Mahon and Low, 1972), the FF day growing season requirement for cotton in temperate areas must take into account the thermal value of the time period. McMahon and Low (1972) proposed that cotton requires 3000 GDD (base 10 ^{0}C) for maturation but higher solar radiation can compensate for less GDD. As was discussed earlier in this chapter, GDD calculated with a base temperature of 12 ^{0}C is now generally accepted in Australia and Hearn (1981) suggests a GDD (base 12 ^{0}C) requirement of 2000 for the growing season.

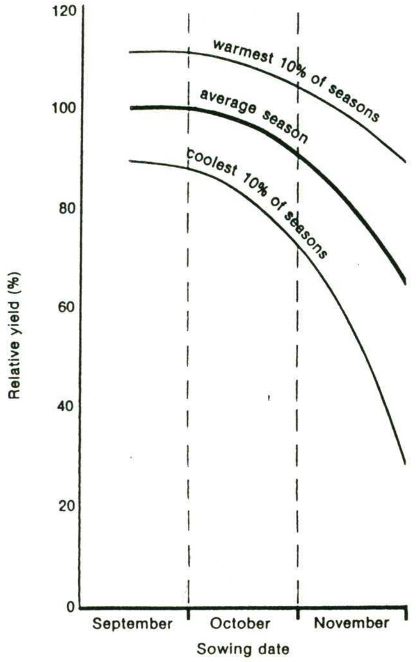
Table 2.4.2: Day Degree Requirements for Bud and Boll Development[1]

	GDD	Days	
		@ 22 ^{0}C	@ 27 ^{0}C
Initiation to 3 mm	200	22	15
3 mm to anthesis	300	30	20
Anthesis to maximum size	310	31	21
Maximum size to mature	365	37	24
Mature to fully open	75	8	5

[1] Source: Hearn and Constable (1984).

With no cotton growth below 12 ^{0}C (Constable, 1976a) and a minimum of 14 ^{0}C required for germination, the current planting practice is Australia is to sow when minimum soil temperatures reach 14 ^{0}C for at least three consecutive days. Earliest sowing dates in most Australian cotton production regions are mid to late September with no decline in yield due to delayed planting until late October (Constable *et al.*, 1976) (Figure 2.4.1). The end of the growing season is marked by the date of first frost and management of the crop is geared towards full maturation before that date.

Figure 2.4.1: Relative Yield Depletion With Delayed Planting of Cotton
Source: Constable (1988b)



With the optimum temperature for growth of approximately 32 ^{0}C (Hesketh and Low, 1968) and rapid growth in the temperature range of 20 - 35 ^{0}C (Hearn, 1969b), it can be expected that with the longer and hotter the season the higher the potential yield. The relationship of accumulated GDD to lint yield has been studied by a number authors including Bilbro and Ray (1973); Constable (1976); Constable *et al.*, (1976); Hughes (1964); McMahon and Low (1972) and Peng *et al.* (1989).

To maximise use of available GDD for a production area, early planting is essential (Hughes, 1964). However, planting of cotton before temperatures rise to optimum for growth can result in an increase in time to first square and hence the crop loses the advantage of earliness (Constable, 1976; Moraghan *et al.*, 1968). In plant breeding for earliness, an important character to select for is cold tolerance, since the ability to germinate and grow under less than optimum temperatures is important is decreasing the time to squaring. Delayed planting decreases the overall available accumulated GDD and hence limits yield potential and reduced lint ginning turnout percentages, fibre length and fibre micronaire (Bilbro and Ray, 1973; Wells, 1992).

Fruiting and fibre development are affected by temperature and varieties differ in their tolerance of low temperatures at various stages in development. Gipson and Joham (1968a) document reduced relative fruit numbers for an Acala variety compared to a shorter season variety when grown with night temperatures between 8.8 and 14.4 ^{0}C; they determined that peak fruiting occurred at night temperatures of 14.0 - 19.4 ^{0}C. Relative fruit numbers increased in both varieties as temperature increased. Decreased night temperatures increased the boll period. The rate and amount of cellulose synthesis decreased with decreased night temperatures and lint was characterised by poor quality, with fibre micronaire being reduced by decreasing night temperatures. Maximum fibre length was attained with night temperatures of 15 - 21 ^{0}C. Constable (1976) found fibre micronaire to be reduced by late crop planting and especially in longer season varieties where bolls were maturing at lower temperatures.

Leaf Area Development

Leaf area is important in determining the quantity of carbohydrate produced. As the plant develops, each node on the main stem and branches subtends a leaf. In the absence of stress, individual leaves gain their maximum size 2-3 weeks after unfolding (Constable, 1986a). They become net exporters of carbon 7 days after unfolding but do not become net exporters of nitrogen until fully expanded with a maximum rate at approximately 21 days of age (Brown, 1973). They remain net exporters of carbon and nitrogen till senescence at approximately 70 days. Maximum sized leaves are found in the middle of the canopy (Constable, 1986a). The importance of leaf age in whole canopy and productivity considerations has been discussed by Wullschleger and Oosterhuis (1990).

Leaves appear regularly at an average interval of 41 growing day degrees or 2.9 days (Constable, 1986a). Leaf area increases in a sigmoid pattern with peak leaf area occurring 3-5 weeks after flowering begins. Leaf area index varies from 0.5 for a severely water stressed crop to 6.0 for a well fertilised and irrigated crop under optimum climatic conditions (Hearn and Constable, 1984). As the leaf canopy develops the ability to support a boll load increases correspondingly.

Studies by Ashley (1972), Benedict and Kohel (1975) and Constable and Rawson (1982) with ^{14}C labelling showed that each leaf supports the development of its nearest vegetative parts. Each leaf on a fruiting branch leaf supports predominantly the fruit form subtended from the same node. When assimilates produced by the leaf closest to a boll decreases e.g. due to shading, there may be increased movement of assimilates from other parts of the plant (Brown, 1973). The percentage of assimilate produced by the subtending leaf transferred to the boll depends on its age. Young squares are at a disadvantage in the first week of unfolding of its subtending leaf on a fruiting limb, as the expanding leaf has the competitive advantage for assimilates and the square is often shed (Constable and Rawson, 1982).

Light and Photoperiodism

The heavy selection pressure used in the development of Upland cotton and most cultivated cottons grown commercially in the temperate areas has removed any of the photoperiodic tendencies of the plant, such that all commercial lines are now considered day neutral. Cottons displaying photoperiodism are those requiring short days for flowering, eg. tropically native cottons which remain vegetative through the wet season (long days) and produce fruit to mature in the dry. These cottons remain vegetative when grown in temperate areas. The Upland types, in contrast, will readily fruit when planted in the tropics and hence, are strongly day neutral (Brown and Ware, 1958).

The intolerance of shading and the high solar radiation requirement of cotton probably explains the fact that the larger proportion of high yield cotton is grown in temperate areas with annual rainfall of less than 1500 mm (Thomson, 1975) and under supplementary or full irrigation.

Fruit Shedding

Squares and young bolls in cotton are commonly shed or dropped from the plant. The mechanism of shedding is described by Brown and Ware (1958) and Guinn (1986). An abscission layer exists across the base of the peduncle of the fruit and is visible as a slight groove. At this position, the division cells are only one layer thick. Under the appropriate stimulus, these cells divide from the periphery inward with each cell dividing only once. The dividing wall between the daughter cells splits immediately along its middle lamella. As a result, the two daughter cells separate instead of remaining united and the continuity of the tissue is destroyed. The fruit remains connected to the peduncle by only the vascular tissue of the wood which breaks under mechanical forces and then abscission is complete. A small callus or scar forms on the peduncle at the site of the abscission.

Shedding may be due to injuries to either the roots or the top portion of the plant by insects, diseases, or mechanical damage during cultivation or storms. But is also a natural physiological response of the plant. Natural shedding is proportionally low during the early part of the season but increases through the season. It is high during flowering, but flowering usually exceeds shedding. As the boll load develops, the proportion of fruit shed increases and finally outnumbers flowers set as bolls as the plant reaches cut out (Hearn, 1981).

A number of physiological responses including hormonal changes are involved in natural shedding and the activation of the abscission process (Guinn, 1986). Water deficit or waterlogging, reduced light intensity through shading or cloudy weather, unbalanced nutrients especially nitrogen, all accelerate shedding. In cotton production, we are interested in overall yield i.e. boll set, rather than on the amount of shedding. Shedding is part of the process by which cotton exists under xerophytic conditions (Hearn, 1981). Cotton will continue to flower until the capacity of the plant is reached, renewing the flowering phase after interruptions due to water stress and continuing growth to replace fruit forms it has shed.

Hormones in Cotton Physiology

The role of plant hormones in the development and flowering of cotton is reviewed briefly in Appendix 2.4.

2.5: Agronomy of Cotton

Morphological and physiological traits of cotton which give it the ability to adapt to a wide range of environments include (i) deep root system, (ii) a dynamic fruit shedding ability, and (iii) growth indeterminancy. These characteristics stem from the xerophytic ancestry of the cotton plant and assist in conferring drought tolerance to the plant. If conditions become unfavourable, the plant is able to draw water from deep in the soil profile or shed squares and young bolls, or go into near dormancy. When conditions become more favourable, growth can be resumed and a higher proportion of fruit retained. Hence, cotton is able to be produced in arid areas and in areas of infrequent rainfall and on a range of soil types (Brown and Ware, 1958).

Soils

Worldwide, cotton is produced on a wide range of soils ranging from sandy loams to clays, provided that they are fertile and well drained. Hearn (1981) found that the common characteristics of the soils used in cotton production are that the pH of such soils range from 5.5 to 8.0 and within that pH range the main criteria for suitability of soils appears to be a depth of at least 0.6m and freedom from prolonged waterlogging. Brown and Ware (1958) state that within the areas climatically suited to cotton, the only soils not used for cotton production are those which are shallow or stony, poorly drained or soils which are low humic or ground water podsols, very sandy or clay pan soils or are topographically unsuitable.

In Australia, the majority of cotton is grown on cracking clay soils or Vertisols[2] (grey and brown clays and black earths[1]), which are moderate to deep clay soils with high available water capacities of 160 - 180 mm. Clay loams (red brown earths, solonized solonetz and solodic soils i.e. Alfisols[2]) are predominantly used for production in the Macquarie Valley and in limited areas of the Namoi Valley, some of these have water holding capacities of less than 150 mm. Recent alluvials or Entisols[2] occur along the river systems of the production areas and are also used for cotton production (Daniells and Larsen, 1991). A summary of soils used in Australian cotton production is presented in Table 2.5.1. Apart from nitrogen deficiency, nutrient deficiencies are not a problem in these soils to date (Daniells and Larsen, 1991). Management of these soils in terms of maintaining soil structure and long term fertility, minimising compaction, and prevention of salinity problems in the long term, form the base of strategies developed for the management of these soils (McKenzie *et al.*, 1995).

Temperature

The temperature requirements of cotton are reviewed in Section 2.4 of this Chapter.

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[1] Great Soils Groups (Australian Classification)
[2] United States terminology

Table 2.5.1: Areas of Cotton and Major Soil Types in the Cotton Growing Localities of New South Wales.

Locality	Area (ha) of irrigated cotton in 1991/92	Soil Type	Approx. % Cotton on Soil Type	Soil Parent Material
Gwydir Valley	73,000	Grey and Brown Clays Loams - clay rich subsoil Loams - no clay rich subsoil	80 10 10	Alluvial plains of mixed origin Slightly elevated ridges in clay plains soils Recent alluviums
Namoi Valley	45,500*	Grey and Brown Clays Loams - clay rich subsoil	90 10	Alluvial plains of mixed origin Slightly elevated ridges in clay plains soils
Macquarie Valley	33,000	Grey and Brown Clays Loams - clay rich subsoil Loams - no clay rich subsoil	60 30 10	Alluvial plains of mixed origin; less basaltic influence than Namoi, Gwydir. Recent Alluviums
MacIntyre Valley	29,000*	Grey Clays	100	Alluvial plains of mixed origin
Bourke	8,600	Grey Clays	100	Flood plain of the Darling River
Walgett	7,000	Grey Clays	100	Flood plain of the Barwon/Darling Rivers
Breeza/Spring Plains	6,000	Black Earths	100	Alluvial plains of basaltic origin
Lake Tandou	4,800	Grey Clays	100	Alluvial plains of mixed origin
Lachlan Valley	1,400	Grey Clays	100	Alluvial plains of mixed origin

* Includes a small proportion of rain fed cotton.

Source: McKenzie *et al.* (1995).

Water and Irrigation

Cotton may have many xerophytic characteristics but is widely grown as an irrigated crop. Reported rainfall requirements of cotton vary depending on economic yield and supplementary irrigation. Cotton grown under irrigation is, of course, higher yielding; world average yields under irrigation and rain-fed cultivation were calculated by Hearn (1995) to be 854 kilograms of lint per hectare and 391 kilograms per hectare respectively. Irrigated cultivation produces approximately 73% of the world's cotton lint.

Hearn (1995) states that the literature on plant responses to water stress at different growth stages are conflicting. He cites Reddell *et al.* (1987) stating that the early flower period was found to be the most sensitive to stress, whereas Orgaz *et al.* (1992) state that cotton yield is most severely affected by severe water stress during peak flowering, and de Kock *et al.* (1993) conclude that the most pronounced inhibiting effect stress had on yields was during boll development after the end of effective flowering. Under modern cotton production practices, the highest lint yields are achieved by matching the rainfall or applied water to the periods of peak water use by the crop. The principles described by Hutchinson *et al.* (1958), Hearn (1988, 1990) are applied in planting the crop at a date to maximise the water available to the crop according long term climatic data.

Hearn (1988, 1990) in assessed the risk of planting rain-grown cotton in a series of Australian cotton production areas, and outlined strategies to lower the risk of crop failure. Such strategies include planting on a defined minimum soil moisture depth specific to the area and soil, not planting before the occurrence of a defined minimum planting rain event, and that in some regions later season rainfall can be utilised by delaying planting.

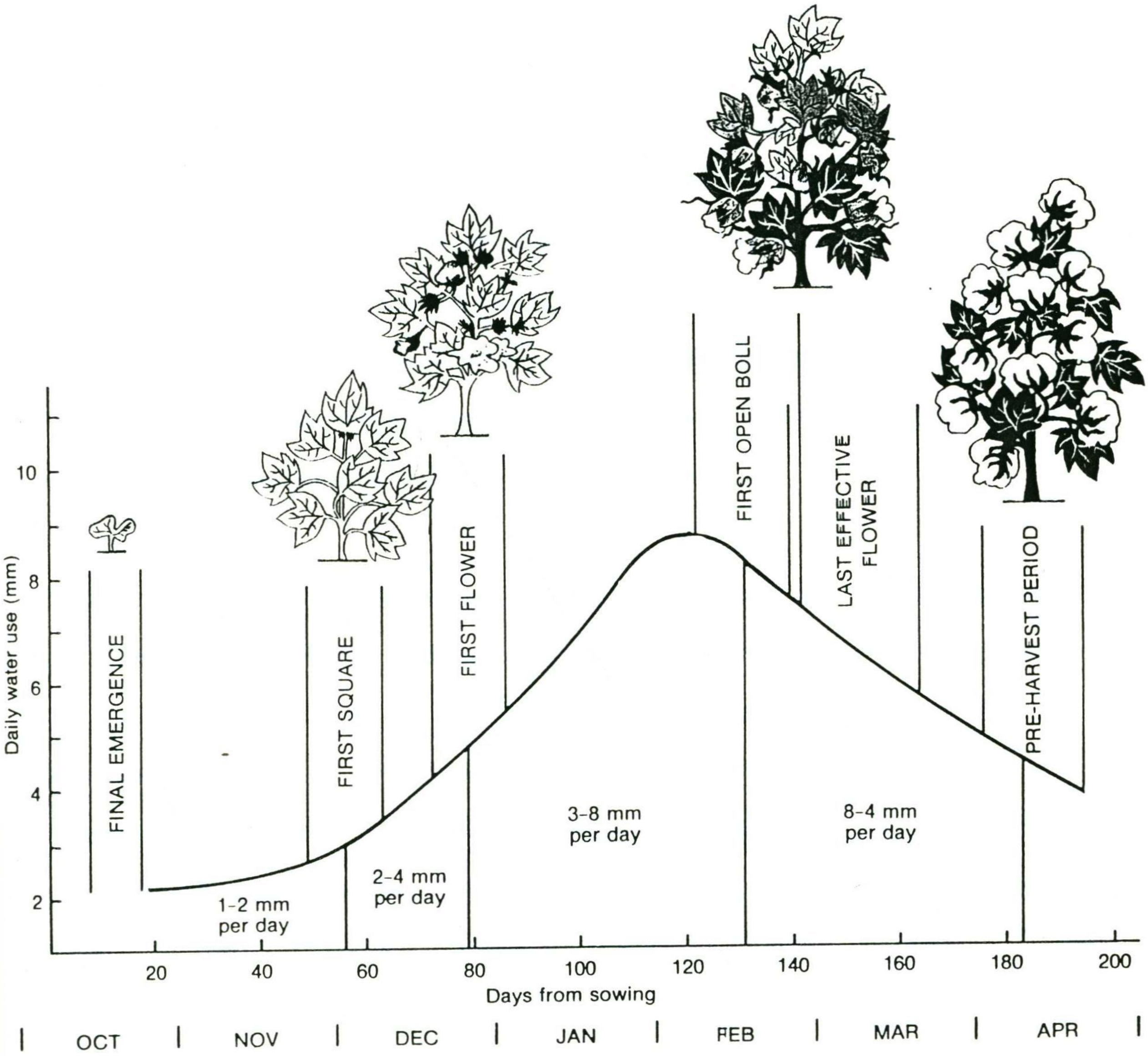
94% of the world's cotton is irrigated by surface irrigation (i.e. flood or furrow). The remaining areas are irrigated by centre pivot, lateral move or drip irrigation systems (Hearn, 1995). Although surface irrigation is labour intensive and inefficient in terms of water loss by evaporation etc., it is the most suitable means of irrigation in many areas due to soils. In Australia, for example, the heavy clay Vertisol soils have a low saturated hydraulic conductivity and so losses from deep drainage are not a problem, with laser levelling of fields, irrigation efficiencies of 75% are achievable (Cull *et al.*, 1986). On lighter soils and shallow soils, drip systems may give improved efficiency by placement of water in closer proximity to the plant and with more accurate quantities of water applied, loss of water by deep percolation can be prevented.

The water requirements of a crop vary with location and season and are determined by the climatic conditions such as sunlight, temperature, wind and relative humidity. In the Namoi Valley in Australia, the water requirement of a well developed medium maturity cotton variety in that area would normally be between 600 and 750 mm which would be supplied by irrigation, rainfall and stored soil moisture (Browne, 1984). Daily crop water use for the same crop is described in Figure 2.5.1. Maximum water requirement occurs during late flowering and early boll fill.

Traditional methods of determining when to irrigate and how much water to apply include rules of thumb for crop appearance and soil moisture condition such as foliage colour and feel, internode length and colour, soil sampling at depth, determining the number of days elapsed since the last irrigation and adjusting for rainfall (Browne, 1984). Standard methods of irrigation scheduling now include the use of neutron probes to measure soil water, pressure chambers to measure Leaf Water Potential (LWP) and infra-red thermometers to measure canopy temperature along with plant and water balance computer models (Hearn, 1995) and are briefly described in Appendix 2.5.1.

Figure 2.5.1: Daily Crop Water Use for Cotton Grown at The Australian Cotton Research Institute, Narrabri, Australia.
(Planting - October, Harvest - Late April)

Source: Browne (1984)



Fertiliser Requirements

In modern cotton production, nutrients are supplied to a crop from the soil and from applied fertilisers. The amount supplied by the soil is influenced by the amount returned to the soil in crop residues versus the quantity removed with the crop product and the cropping history of the field. If residues are burnt, then the non-metallic elements nitrogen, phosphorus, and sulphur are lost to the atmosphere. If residues are incorporated into the soil, they decompose and become available to subsequent crops. Hence, of the elements taken up in large quantity by a cotton crop, N and P are more frequently needed as fertilisers than K, Ca and Mg (Hearn, 1981). Hearn (1981) reviewed the nutrient requirements of cotton, deficiency symptoms, critical levels, plant tests and nutrient application. A summary of uptake of nutrients by cotton and nutrient removal is presented in Table 2.5.2.

Fertiliser requirements vary with soil type, history of cultivation and type of production and hence are site specific. Maples and Keogh (1965) identify nitrogen as the first limiting factor to yield in regard to fertilisers. Dry matter accumulation, leaf area, canopy photosynthesis and ultimately lint yield are strongly related to available nitrogen (Wullschleger and Oosterhuis, 1990; Bondada *et al.*, 1996). Nitrogen fertilisation increases yields by prolonging growth and increasing the number of bolls set i.e. delays cut out. Increasing applied nitrogen above an optimum level was found to induce excessive vegetative growth and delayed maturity, and this finding is also reported by Basinski *et al.* (1975), Constable and Rochester (1988), Hearn (1981), Thomson (1975). Excess nitrogen was also found to carryover to following crops and the importance of more accurate application rates using soil tests and petiole analyses was stressed by Maples and Frizzell (1985).

Constable and Rochester (1988) investigated the uptake of nitrogen by the crop and developed yield response curves for nitrogen (Figure 2.5.2). Early uptake of nitrogen is rapid and in excess of the plant's requirement at that time. The leaf canopy acts as reservoir of nitrogen, as plant nitrogen requirements increase to a peak in early boll set, nitrogen is re-mobilised from the leaves to supply young fruit. Fertilisation programs are designed to have nitrogen applied and available to the plant at times to match peak requirements. As nitrogen is stored in the leaves and then re-mobilised for use by growing bolls, nitrogen needs to be applied approximately three weeks before peak usage. Hence, current Australian recommendations (Constable, 1986, 1988, 1990) are to apply all nitrogen prior to the first irrigation so that nitrogen is available to the plant for its peak requirement period which corresponds to early January in the Namoi Valley of Australia.

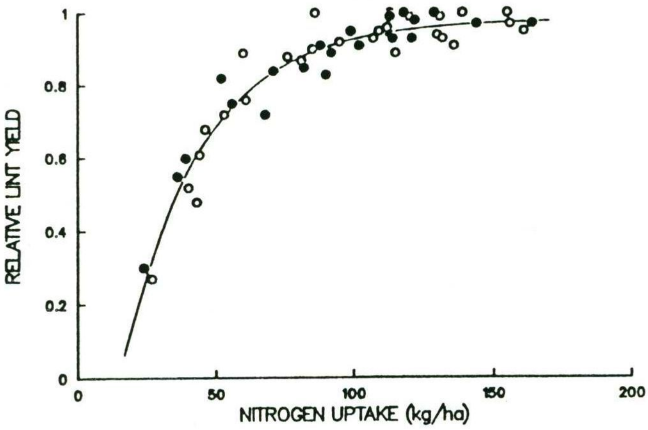
Table 2.5.2: Essential Nutrients for Cotton and Typical Values for Total Plant Uptake and Removal at Harvest

	Typical Uptake kg/ha	**Typical Removal* kg/ha**
Nitrogen	110	11
Potassium	125	6
Phosphorus	30	2
Calcium	90	1
Magnesium	30	1
Sulphur	10	0.1
Iron	0.600	0.066
Manganese	0.450	0.012
Boron	0.200	0.021
Zinc	0.060	0.013
Copper	0.020	0.003
Molybdenum	0.003	Trace

* Removal refers to that removed by a crop including seed and lint, assuming a 38% gin out turn.

Source: Constable (1988).

Figure 2.5.2: Relationship between N Uptake and Relative Lint Yield
Source: Constable and Rochester (1988)



Relationship between N uptake and relative yield; pooled data for the five experiments. Relative yield (RY) is the yield of each treatment as a proportion of maximum yield in that experiment. Solid circles denote N applications before sowing, open circles denote treatments where at least some N was applied after sowing. The equation for the curve is: $RY = 0.981 \pm 0.012 \{1 - \exp[-0.0343 \pm 0.0029(N - 15.0 \pm 1.8)]\}$; $R^2 = 0.98$.

Following a crop rotation eg. cotton/wheat or fallowing, more nitrogen is found in the soil and available to the crop and reduced fertiliser is required (Constable *et al.*, 1992). In contrast, nitrogen recovery from fertiliser is reduced by denitrification, leaching and ammonification (Humphreys *et al.*, 1988) waterlogging and water stress (Hearn and Constable, 1984) and requirements may increase. Current nitrogen fertiliser recommendations for Australian crops are presented in Table 2.5.3. The rates suggested allow the cotton crop to take up enough nitrogen to achieve full yield potential without severely affecting the date to maturity or the fibre quality. Timing of nitrogen fertiliser application becomes important in maximising the availability of nitrogen to the crop i.e. minimising loses due to denitrification etc., while minimising fertiliser input (Constable, 1987).

Table 2.5.3: Average Nitrogen Application Rates For Cotton After Various Crop Rotations[1]

Previous Crop	Nitrogen Rate (kg/ha)
Cotton or Sorghum	130-160
Third Year Cotton	150-180
Soybean	80-110
Wheat	70-100
Fallow	60-80
Factors Which Increase These Rates: - long growing season - compacted soil - heavy, flat country	Factors Which Decrease These Rates: - river loam soils - short season - good soil structure

[1] Source: Constable (1988c)

Nitrogen fertiliser is predominantly applied in the form of anhydrous ammonia placed under the hill during the winter fallow. Other practices are to use urea or ammonium nitrate, with either the total amount required placed under the hill prior to planting or a split application with part placed under the hill prior to planting and the remainder side dressed early in the season. Water-run nitrogen where anhydrous ammonium is injected into irrigation water has been used to some degree although large losses of N occur due to volatilisation; water-run urea is a more efficient form of N for this type of fertilisation (Constable, 1987). Foliar application of nitrogen is used to overcome short term nitrogen deficiencies such as that due to waterlogging but it is not possible to apply large quantities of nitrogen is this manner (Constable, 1987). Soil nitrogen testing and petiole testing are widely used to optimise nitrogen application and methods are reviewed by Burhan and Babikir (1968), Constable (1987, 1988a and c, 1992), Constable *et al.* (1991) and Hartizan (1988).

Although U. S. soils are found to respond to applied phosphorus and potassium in some areas (Maples and Keogh, 1965), phosphorus is rarely a primary cause of yield reduction world-wide (Hearn, 1981). Available levels of phosphorus in Australian cotton growing soils is quite high and a deficiency of this nutrient is not considered a problem. Phosphorus is part of the mineral complex of most of the cotton production soils. Exceptions are some soils of the St. George, Emerald and of the Dawson-Callide and Macquarie Valleys where phosphorus levels are low (Daniells and Larsen, 1991).

Potassium is generally high is Australian soils but with continued cropping to cotton deficiencies are developing on some soils (Harden, 1994; Harden and Wilson, 1994; Oosterhuis, 1994; Oosterhuis, 1995).

Trace elements seem to be present in adequate levels in Australia with the exception of zinc which can become unavailable due to specific soil conditions, e.g. in areas cut in laser levelling, high pH soils or fields displaying long fallow disorder (Constable, 1988a; Daniells and Larsen, 1991).

Defoliation, Harvesting and Ginning

Defoliation, harvesting and ginning of cotton crops is discussed in Appendix 2.5.2.

Disease of Cotton

Australia has comparatively less cotton diseases than more tropical production areas and than those listed as causing losses in the United States (Watkins, 1981). Those diseases found in Australia cause large economic losses under conditions inducive to the build up of the causal pathogen. Allen (1990) lists the diseases of most economic importance in Australia to be seedlings diseases (e.g. *Pythium* sp., *Rhizoctonia sp.*), bacterial blight (*Xanthomas campestris* pv *malvacearum*) and verticillium wilt (*Verticillium dahliae*); whereas boll rots (e.g. *Fusarium* sp.) and Alternaria leaf spot (*Alternaria macrospora*) are recorded as causing losses under specific conditions.

Seedling disease encompasses disease problems ranging from seed rot, to watery rot of the hypocotyl commonly called damping off, root pruning, brown lesions at the stem base or collar rot and leaf spotting of the cotyledons (Allen, 1988). It is commonly referred to as the "seedling disease complex" due to the number of pathogens involved and their relative importance depending on climatic conditions. Of the pathogens involved the most important are *Pythium*, *Rhizoctonia* and *Fusarium* spp. The cotton seedling is susceptible to attack during germination and emergence and any weather or seed bed condition which are detrimental to the rapid emergence of the seedling makes it more susceptible to disease. In wet or cold planting seasons, seedling disease is the cause of a large proportion of replanting (Allen, 1988). Control of seedling disease is by use of seed dressing and providing optimum seed bed and climatic conditions for germination and growth of the seedling.

Recently black root rot (*Thielaviopsis basicola*) has began to develop as a problem seedling disease in the Namoi Valley in Australia. Although known worldwide as a disease of seedling and mature plants, it was not identified in cotton in Australia until 1988 (Honess *et al.*, 1994). It is characterised by black lesions or total blackening on root tissue, and hence seedlings display generally low vigour, resulting in delayed maturity and loss of production. Infection is favoured by cool temperatures and moist soil conditions, and with a wide host range and survival structures, chlamydospores, the fungus is able to survive for long periods in the soil. Late infection of mature plants can occur when temperatures decline and symptoms include a swelling of the base of the stem caused by the destruction of internal tissue and production of chlamydospores within the tissue.

Bacterial blight (*Xanthomas campestris* pv *malvacearum*) has caused significant yield losses in Australia in susceptible cotton varieties over the last two decades (Allen, 1988). The bacterium is seed borne but spread in water splash and hence epidemics quickly build up in humid stormy conditions common is many parts of the Australian cotton growing areas during summer. The disease is characterised by angular lesions on the leaf (i.e. Angular Leaf Spot stage of the disease), lesions on bolls preventing the boll developing fully or at the base of bolls preventing it opening. Early severe symptoms can include blackening and death of infected stems or limbs (i.e. Black Arm). With the introduction of a blight control program to minimise seed contamination and the widespread use of resistant varieties, the incidence of Bacterial Blight has been dramatically reduced since 1986 (Allen, 1988).

Verticillium wilt (*Verticillium dahliae*) is a major disease in most of the world's cotton production areas (Watkins, 1981). It is a soil borne fungus with a wide host range and survives for long periods in the soil due to the production microsclerotia (resting bodies) in plant debris. Incidence of the disease is highest in the areas with the longest history of cotton cultivation and uncommon is newer production areas. Control relies on the use of tolerant varieties and current Australian breeding programs are beginning to release lines with tolerance to the disease (Allen, 1988).

Alternaria leaf spot (*Alternaria macrospora*) of cotton is recorded spasmodically in Australia, in most cases causing a minor leaf spot. On occasions, it has caused severe defoliation and yield loss on occasions (Allen and West, 1988, Allen 1990).

Fusarium wilt (*Fusarium oxysporum* f.sp. *vasinfectum*) whilst recorded as causing widespread and severe losses in the United States for over a century (Hillocks, 1992; Watkins, 1981), was not recorded as a disease of cotton in Australia until 1993 (Kochman *et al.*, 1994). Disease surveys in 1993 revealed farms in the Darling Downs area had high infection levels of plants displaying the typical wilt with extensive brown discolouration of the vascular system, with leaf and stem death often starting from the top of the plant (Kochman *et al.*, 1994). Hillocks (1992) states that the disease can occur at any stage of crop growth but more usually they are seen in the adult plant during boll formation and filling. The extent of the spread of this disease depends on quarantine measures, maintaining the cotton seed sources free of the disease and the screening and use of varieties displaying tolerance or resistance to the disease.

Insect Pests

As cotton is primarily grown as an irrigated crop in Australia. It is highly attractive to insect pests for a large part of its growing season and with the high economic value of cotton lint, insect control is of major importance. Cotton is attacked by a range of insects pests which cause large losses in production in many parts of the world. In Australia, over thirty species are listed as attacking cotton (Forrester and Wilson, 1988) as presented in Tables 2.5.3a & b. *Helicoverpa punctigera* (native budworm) and *Helicoverpa armigera* (cotton bollworm) are considered major pests and are active throughout the growing season, with *H. punctigera* being predominant in the early season, and *H. armigera* active mid to late season. Insect control programs in Australian cotton revolve round the control of the two insect pests. Also of major importance are *Earias huegeli* (rough bollworm), *Tetranychus urticae* and *Tetranychus ludeni* (two spotted and spider mites), *Thrips imaginis* and *Thrips tabaci* (thrips). *Aphis gossypii* (aphids) and *Crocidosema plebeiana* (tipworm).

Early control measures relied on the heavy usage of chemicals such as DDT, and also monocrotophos, dimetron-S, methyl and ethyl parathion and endrin. The build up of resistance by *Helicoverpa* sp. to DDT (Wilson, 1974; Goodyer *et al.*, 1975 as cited by Thomson, 1975) and other chemicals saw increased chemical usage in all cotton areas and the final abandonment of cotton production in some areas such as the Ord River Valley in North Western Australia.

With the increased cost of chemicals, environmental concerns and the build up of resistance by the insect pests to insecticides, current insect control measures are based on extensive research and integrate minimised chemical usage and rotation of chemicals with cultivation, use of beneficial / predatory insects and biological insecticides. In the future, cotton, genetically engineered for resistance to pest attack may form part of the integrated pest management system and assist in lowering chemical usage in cotton and prolonging the life of the insecticides which remain part of the program (Fitt, 1994).

Table 2.5.3a: Major Insect Pests of Cotton In Australia.

Major Pests of Cotton

Pest	Damaging Stage	Plant Part Damaged	Seasonal Incidence	Comments
Helicoverpa punctigera (Native budworm)	Larvae	Terminals, buds, flowers, bolls	Early to mid	This is a key pest species. All spray programs are based on controlling this pest. It bores into fruiting parts causing tem to drop off or rot. Larger bolls can be completely hollowed out.
Helicoverpa armigera (Cotton bollworm)	Larvae	Terminals, buds, flowers, bolls	Mid to late	This is a key pest species. As for native budworm. This species has developed resistance to chlorinated hydrocarbons, pyrethroids and some carbamates.
Earias huegeli (Rough bollworm)	Larvae	Terminals, buds, flowers, bolls	Early to Late	It attacks terminals and leaf axils in young plants causing malformation. Later, it attacks by boring into squares and bolls. Fungal or bacterial rots aggravate damage.
Tetranychus urticae (Two Spotted Mite) *Tetranychus ludeni* (Spider mite)	Nymphs and Adults	Leaves	Mid to Late	It is present from seedling emergence, although generally in low numbers with populations increasing from mid to late season. It feeds mostly on the undersides of leaves causing loss of photosynthetic area. Leaves often develop red pigmentation and bronzing. Cotton mites are resistant to organophosphates, but control is still possible with certain organophosphates.
Thrips imaginis and *Thrips tabaci* (Thrips)	Nymphs and adults	Terminals, leaves	Early	They feed by lacerating soft tissues and sucking up plant juices. Leaves become distorted and silver on the underside; terminal buds become blackened and die. Damage is greatest when dry weather in spring forces thrips off their normal hosts onto cotton seedlings.
Aphis gossypii (Aphids)	Nymphs and adults	Terminals, leaves, buds, stems	Early to late	They feed by piercing and sucking. Outbreaks sometimes occur on seedlings causing stunting. Heavy infestations at the end of the season produce copious amounts of honeydew which can foul lint. Female aphids lay only live young.
Crocidosema plebeiana (tipworm)	Larvae	Terminals, stems	Early	Newly hatched larvae graze in the terminals, then later tunnel down the stem. Their main damage is to delay maturity, which may or may not be a significant problem depending on seasonal and agronomic factors. Tipworm problems are correlated strongly with the prolific winter growth of its host marshmallow, *Malva parviflora*.

Source: Adapted from Shaw (1994) and Forrester and Wilson (1988)

Table 2.5.3b: Sporadic Pests of Cotton in Australia

Sporadic Pests of Cotton	
Early Seedling	*Agrypnus variabilis* (True wireworm) *Pterohelaeus darlingensis* (False wireworm) *Gonocephalum macleayi* (Southern false wireworm) *Saragus sp.* (False wireworm) *Agrotis spp.* (Cutworms) *Smynthurodes betae* (Bean root aphid) *Spodoptera exigua* (Lesser army worm) *Loxostege affinitalis* (Cotton webspinner) *Frankliniella schultzei* (Tomato thrips) Order Collembolla (Springtails) Sub-family Halticinae (Flea beetles) *Austracris guttulosa* (Spur throated locust) *Teleogryllus spp.* (Field crickets)
Late Seedling to Squaring	*Austroasca viridigrisea* (Vegetable leafhopper or jassid) *Creontiades dilutus* (Green mirid) *Campylomma livida* (Apple dimpling bug or yellow mirid) *Taylorilygus pallidulus* (Broken back bug) *Bucculatrix gossypii* (Cotton leaf perforator) *Anomis flava* (Cotton looper)
Boll Production/Maturation	*Myzus persicae* (Green peach Aphid) *Trialeurodes vaporariorum* (Greenhouse whitefly) *Bemisia tabaci* (Whitefly) *Dysdercus sidae* (Cotton stainer) *Tectocoris diopthalmus* (Cotton Harlequin Bug) *Nezara viridula* (Green Vegetable Bug) *Oxycarenus luctuosus* (Cotton Seed Bug)

Source: Adapted from Shaw (1994) and Forrester and Wilson (1988)

2.6: Hail Damage in Agricultural Crops

Hail storms cause damage and losses in many agricultural crops. Hail injury to crops may consist of stand reduction, defoliation, stem cut off or bruising, inflorescence damage, and fruit damage or removal. The effect of the damage varies with the crop type and the severity, type and timing of the hail damage. Crops may compensate to some degree for hail damage by renewed vegetative and reproductive growth after hail damage. This compensation is also dependent on the crop type and the severity, type and timing of damage and on the seasonal growth conditions available to the crop.

Early studies on hail damage (Johnson, 1972; Kalton *et al.*, 1949 and Lane, 1959) looked at the response of crops to the separate symptoms of simulated hail damage and then combined the simulated symptoms as a means of measuring and estimating the overall effect of hail damage on a crop. Kalton *et al.* (1949), working with soybeans (*Glycine max*), found variable effects of injury on yield at earlier stages of growth and concluded that recovery depended on environmental conditions post damage. Losses increased progressively through to the beginning of seed development in pods. After this stage, losses became progressively less as the stage of development advanced. Loss at the last stages of growth was purely due mechanical severity as losses were the result of pod removal and no regrowth occurred.

Johnson (1972) found that sunflowers (*Helianthus annuus*) can tolerate some leaf loss without a yield depletion if leaves are lost from the lower part of the plants (i.e. early growth stages) or the smaller leaves at the top of a more mature plant. Removal of leaves in the middle section of the plant caused dramatic loss in yield and it was concluded that these leaves were of greater importance in supplying photosynthates to the developing inflorescence.

Lane (1959) in quantifying the effect of the separate symptoms of hail damage in cotton (*Gossypium sp.*) on lint yield, found that of the symptoms inflicted by the simulation of hail, reduction in plant density did not reduce yield until plant numbers dropped below optimum plant populations or with damage occurring at late stages of development. Complete defoliation had a significant effect on lint yield when it occurred from the flowering stage onwards. Stem bruising was a recoverable injury but lint yield loss was highly correlated with timing and position of stem cut offs, with the cotton able to recover from early season low cut offs, whereas severe yield depletions occurred with later season stem cut offs.

The initial work of Johnson, (1972); Kalton *et al.*, (1949) and Lane, (1959) showed that level of yield reduction is highly correlated with stage of crop development at the time of damage for various crops and a critical stage for defoliation would correspond to early reproductive development. However, this early work used rather subjective definitions of crop development at the time of damage. With no accurate definition of growth stage, there was no way to directly compare the results of the various research work carried out on hail damage. Accurate stage descriptions are essential in loss adjustment because the amount of yield reduction is directly related to the amount of development at the time of injury.

To standardise descriptions of soybean development for research and for stage determination in loss adjustment after hail damage, Fehr *et al.* (1971) developed objective stage descriptions for soybean suitable for application to both determinate and indeterminate varieties and to all growing conditions. Similarly, stage of development descriptions for corn have been developed by Hanway (1969), for sunflowers by Schneiter and Miller (1981) and for cotton by Elsner *et al.* (1979). These stage descriptions are independent of environmental influences and genotype.

Using standard growth stage descriptions, Teigen and Vorst (1975) studied the effects of stand reduction and defoliation on soybean by simulating injuries at the Vegetative Stage 7 and Reproductive Stage 3 of development. They concluded that soybean can suffer early defoliation without yield loss since leaf material is removed which contributes little to seed production but yield is decreased by damage in later stages of development. Fehr *et al.* (1981) identified the most critical stage of development to be R5 (beginning to seed) or R5.5 for losses due to hail damage for both determinate and indeterminate lines of soybean. The differences in the critical stage for defoliation between Fehr *et al.* (1981), Kalton *et al.* (1949) or Teigen and Vorst (1975) is presumably due to differences in growth staging systems used.

Baldridge (1971) investigating the response of 'Pinto' beans (*Phaseolus vulgaris* L.) to simulated hail damage found strong similarities with the work of Fehr *et al.* (1981) on soybean. Baldridge found that defoliation had the greatest effect at full bloom and least effect at the first trifoliolate stage. Severe early defoliation delayed the onset of full bloom by 4-5 days. Similarly, Schneiter *et al.* (1987) defined the critical stage for defoliation to be the early reproductive stages (i.e. bud development and expansion) in sunflowers. Defoliation at this time caused the most significant loss in yield. Earlier defoliation was less detrimental as the plant has a longer period in which to compensate. The negative effects of defoliation lessened as the R6 stage was reached after anthesis was complete.

Hanway (1969) found that corn plants (*Zea mays* L.) also showed appreciable recovery after defoliation. Similar to soybean, the early reproductive growth stage, i.e. stage 4 of growth (initial stages of tasselling) was the most susceptible to yield loss from hail damage. Yield recovery after hail was found to be highly positively correlated with the quantity of leaf material replaced after defoliation, i.e. the greater the amount of compensatory leaf growth post damage, the lower the yield reduction from the hail damage. Egharevba *et al.* (1976) and Baldridge (1976) confirmed the findings of Hanway (1969) that the critical stage for defoliation in corn was the tasselling period and defoliation at that stage produced the greatest decrease in yield of grain and foliage.

In tobacco (*Nicotiana tabacum* L.), leaf yield and leaf quality are the primary concerns following hail damage. Whitfield (1982) studied the effect of defoliation timing on leaf yield and quality of tobacco and found that the plant compensated for slight and moderate vegetative damage. Yield and leaf quality were most drastically reduced by severe damage at or after flowering when no regrowth was possible or new leaf does not mature.

Thus, from this work, it can be concluded that crops are able to produce compensatory growth after defoliation in the early stages of the growth cycle. Compensation decreases to a minimum at early reproductive stages of development where defoliation causes the greatest yield losses. At later stages of reproductive growth, the effect of defoliation is proportional to the severity of the hail damage and no compensatory leaf growth occurs.

Defoliation is a major symptom of hail damage but other symptoms include stand reduction, stem cut off, stem bruising, inflorescence damage, fruit damage or removal. Stand reduction is common in early growth stage hail damage. Lane (1959) found that in cotton (*Gossypium sp.*), reduction in plant density did not reduce yield until plant numbers dropped below optimum planting populations or with damage at late stages of development. In canola (*Brassica campestris* L.), hail is often experienced in the early stages of establishment. Stands can be reduced to 8 plants/m^2 before yields dropped off dramatically (McGregor, 1987). Reducing the plant number in canola produced increased dry matter accumulation, greater branch number and pod number per plant and delayed plant maturity. Hence, stand reduction by hail in the vegetative stages of growth of the crop lead to plant compensation by a greater production of dry matter per plant and increased fruiting sites and fruit numbers per plant at the expense of crop maturity.

Teigen and Vorst (1975) suggested that increased light penetration into the canopy with the lower plant stand following V7 growth stage stand reduction in soybean allowed crops to compensate for early stage stand reduction by producing an increased number of pods per plant. Yield compensation occurred with early stand reduction of 'Pinto' beans (*Phaseolus vulgaris* L.) , but significant losses occur with stand reduction from full bloom to pod set (Baldridge, 1971).

Actual plant density or row spacing at the time of damage had no effect on recoverability from hail damage in soybean (Burmond and Fehr, 1973), peas (Miller and Muehlbauer, 1984) and corn (Hanway, 1969).

Stem damage is also a contributing factor to hail losses. In 'Pinto' Beans, Baldridge (1971) found stem bruising decreased yield at all growth stages with early stem bruising causing plant death but even slight stem bruising at or around full bloom resulted in yield losses. Miller and Muehlbauer (1984) simulated hail with stem excision i.e. cut-off in 'Alaska' peas (*Pisum sativum* L.) and found plant recovery was in the form of compensatory regrowth from lateral buds but yield reductions were greater in the reproductive stage.

In indeterminate plants such as some soybean varieties and cotton, hail damage may also inflict damage by bruising or cutting off either the main stem or vegetative and fruiting limbs. Compensatory growth after such damage is usually from lateral axillary buds. Severe stem bruising is classified as being equivalent to a direct cut off and the interaction with other damage symptoms in indeterminate crops compounds the yield loss (Fehr *et al.*, 1983). At earlier growth stages, they found stem damage in soybean caused a greater yield loss than defoliation but defoliation became increasingly important as the crop matured so that at R4 and R5 growth stages, when leaf material is supplying assimilates to the fruit load, damage by defoliation resulted in a greater yield loss than stem injury.

Hail damage delays the maturity of crops by delaying development. Early stage defoliation delayed maturity in soybean (Fehr *et al.*, 1984), corn (Baldridge, 1976; Hicks *et al.*, 1969; Vasilas and Seif, 1985), 'Pinto' beans (Baldridge, 1971), 'Alaska' peas (Miller and Muelbauer, 1984), rapeseed (McGregor, 1987) and tobacco (Whitfield, 1982). This delay in maturity may produce problems in harvesting and reduced returns due to immature seed or fibre.

Fehr *et al.* (1977) studied the response of indeterminate and determinate soybean cultivars to defoliation and half-plant cut off and found that the determinate lines displayed consistently greater yield loss after damage. With the development of semideterminate varieties of soybean, Fehr *et al.* (1984) investigated the performance after hail of these varieties to that of indeterminate lines. Simulating defoliation at the R2 or full bloom stage and at the R5 (beginning to seed), yield reduction was greater in the semideterminate lines compared to the indeterminate lines and with earlier (R2) stage damage, the indeterminate line was more delayed in maturity than the semideterminate line. Hence, varietal habit is important in considering loss due to hail in soybeans.

The defoliation studies of Hanway (1969) had shown that earlier season corn varieties showed a greater loss in yield than later maturing lines following defoliation primarily due to a decreased number of kernels, whilst Egharevba *et al.*, (1976) using similar lines could find no differences in yield or dry matter accumulation following damage. Working at a more northern site, Hicks *et al.* (1977) found that the yield losses incurred by corn hybrids corresponded to the loss adjustment charts only for long-season hybrids. Short-season hybrids consistently showed losses ten percent less than the loss charts for moderate levels of defoliation and hence, the short-season hybrids were able to produce compensatory regrowth and mature in the remaining season available following defoliation.

Vasilas and Seif (1985) compared the regrowth after defoliation of a corn hybrid with its parental lines and found complete defoliation at anthesis reduced the yield of all genotypes but the response of the hybrid and inbreds was different in the different seasonal conditions. Complete defoliation before anthesis was found to affect the inbreds more than the hybrids but total defoliation after anthesis affected the hybrids more than the inbreds. They concluded that the hybrids have a longer duration of grain fill and accumulate a greater percentage of kernel dry matter after late milk stage and are more greatly affected by post anthesis defoliation. Drought conditions had an effect on responses to defoliation and Vasilas and Seif (1985) concluded that early stage defoliation increased grain yield by delaying plant development until irrigation water was available. Hence, where defoliation or damage acts to delay the maturity of a crop, it may act to reduce the recovery potential of one variety versus another in shorter season areas, or under conditions such as drought where the later maturing type is disadvantaged.

Crookston and Hicks (1977) reported yield increases after early stage defoliation with early-season corn hybrids such as 'Trojan TX 85', but other reports (Johnson, 1978) could not reproduce the varietal differences in response to early defoliation between early season hybrids and other maturity types. Crookston and Hicks (1988) summarised eleven years of corn defoliation trials in an attempt to solve the discrepancies and found that positive effects occurred in low yield years, i.e. when end of season soil moisture was low, yields were low and responses to defoliation were positive. They suggested that early season defoliation induces the plants to conserve water for post-anthesis growth and may be a tool for management of crops in conditions where late season moisture stress could be predicted. The yield differences measured between varieties of corn in the studies by Crookston and Hicks (1977), and Vasilas and Seif (1985) were responses to environmental conditions rather than differences in recovery of varieties from simulated hail damage.

Procedures for estimating losses must be equally applicable to all varieties of a crop and to all production areas. Hence, the response to hail of different crops types and varieties in different areas needs to be determined.

2.7: Hail Damage Research In Cotton

Research into the effect of hail on cotton crops is limited. Most work is based on crops which have experienced a hail storm (Kittock *et al.* 1976; Peacock and Hawkins, 1974). With the development of insurance policies to protect growers from the financial implications of losses, research involving simulated hail damage was initiated (Cotton Research and Development Corporation, 1990, unpublished). The aim was to measure the effect of different levels of damage on crops at different stages during the growth season.

In cotton, hail damage and hail damage loss assessment was first examined in the 1950s in the United States. As cotton has an indeterminate growth habit and the ability to regrow or compensate after damage by insects, hail etc, it complicates the study of hail damage. Hail damage to cotton is not characterised by one symptom but by the combined effect of a number of injuries to leaf material, stem, fruiting limbs and fruiting structures (Lane, 1959).

Lane (1959) quantified the effect of the separate symptoms of hail damage in cotton on lint yield. The reduction in plant density by simulated hail did not reduce yield until plant numbers dropped below optimum planting populations or with damage at late stages of development. Complete defoliation decreased lint yield when it occurred from the flowering stage onwards. The yield loss associated with stem bruising was highly correlated with the timing and position of stem cut-offs and/or bruising. Crops were able to recover from early season low cut offs but severe yield depletions occurred with later season stem cut-offs. Combining defoliation with other damage symptoms, no additional decreases in lint yield resulted from the overall damage simulation, although 100% defoliation did generally result in greater losses in yield than from injuries separately.

A key requirement for measuring hail damage in cotton was the development of a systematic method of defining the developmental stages of the plant. The development of the cotton plant is defined in four stages of growth for general agronomic use:- vegetative, squaring, flowering or boll development stages of growth. Chronological and thermal time after emergence and the number of fully expanded leaves or number of main-stem nodes have also been used. These stage descriptions can be very subjective and overlap. Elsner *et al.* (1979) defined uniform stage descriptions for upland cotton (*Gossypium hirsutum L.*) which are now generally used in hail simulation studies and in the insurance industry for assessment of crop losses and are described in Chapter 3.

Smith and Varvil (1981) concluded that the recovery of cotton following simulated damage depended on the growth stage at the time of damage. Simulating damage to cotton in the V4, R2 and R5 stages of development, they found that recovery after early season damage was highly correlated with the number of nodes removed in the damage simulations. Recovery decreased with damage at increasingly later stages of development. The decreased yield resulting from mid-season (near flowering) damage was not be related to number of nodes removed or the stage of growth. They suggested that site and year (i.e. seasonal conditions and season length following damage) affect the ability of hail damaged cotton to recover. Field conditions and stresses imposed by diseases such as Verticillium wilt in this case, would also decrease the ability of plants to recover and interact to determine the ability of a crop to recover from later season damage.

Cotton varieties vary in growth characteristics and cotton production areas cover a range of climatic and soil zones. From the work of Fehr *et al.*, 1977 and 1984; Hanway, 1969; Hicks *et al.*, 1977 and Vasilas and Seif (1985), it would be expected that varietal factors come into play in the recovery of cotton from hail damage. Kittock *et al.* (1976) noted large differences between Pima cotton varieties *(Gossypium barbadense L.)* in vegetative growth measured five weeks after hail. But the experiments were not taken through to crop maturity to determine final lint yields. The ranking of varieties on the basis of vegetative regrowth was the inverse of the lint yield ranking in related trials. They suggest that vegetative regrowth was negatively correlated with lint yield. They postulated that the higher yielding varieties displayed lower vegetative regrowth due to the fact that the larger number of immature bolls on these plants acted as strong assimilate sinks and so less assimilates were available for vegetative regrowth.

In contrast, Peacock and Hawkins (1974) reported no difference in lint cotton yields between upland varieties *(Gossypium hirsutum L.)* damaged by hail in the early season. Smith and Varvil (1984) reported a differential recovery between upland varieties damaged by simulated hail in the early season (V2 stage) with a short season variety, yielding better than two longer season varieties. Differences in lint yield were not found after damage later in the season damage. As this work was performed in Arkansas, a short season area, longer season varieties would be disadvantaged by hail damage and the lack of supplementary irrigations (Thomson Pers. Comm.). Crop variety may be an important factor in recovery of cotton crops after damage by hail in some production areas.

2.8: Compensatory Growth in Cotton

Although there has been limited research on the mechanisms of compensatory growth after hail damage, the ability of cotton to regrow and compensate following damage or removal of fruiting forms has been widely studied in respect to damage by insect pests. The regrowth responses to hail described in Section 2.7 are similar to the responses observed following fruit removal or damage by insects. Following is a discussion of cotton plant compensation based predominantly on damage simulation studies carried out for the purposes of developing insect management strategies.

The ability to produce compensatory growth following damage is related to the indeterminate growth habit of the cotton plant, its morphological growth pattern and physiological responses to the removal of all or part of the fruit load.

The indeterminate growth habit confers unlimited morphological growth, as the main stem develops it produces fruiting branches at successive nodes and an ever increasing number of flower buds are initiated which potentially contribute to lint yield (Constable and Hearn, 1984). Development is only restricted by environmental and physiological factors. As carbohydrate and nitrogen supplies become limiting, competition develops between the various growing plant parts and the nutritional dominance of developing bolls sees the cotton plant reduce the rate of morphological development and hence flower bud initiation, flowering and boll set are reduced and fruit that are not set as bolls are shed. Since the plant has reached the maximum boll load that is attainable with the given inputs, square production stops and the plant is termed as having reached "cut out" (Constable and Hearn, 1984). As some fruit mature and no longer act as sinks for assimilates, the plant may restart growth and produce a second fruiting phase.

The natural fruit shedding characteristic and the ability to resume morphological development as conditions become more suitable, enables the cotton plant to compensate for periods of limited supply of plant requirements and also compensate for loss of fruiting forms due to insect attack or other forms of damage (Hearn, 1979).

Fruit removal or disbudding of cotton plants is consistently found to increase vegetative growth and concurrently increase floral bud initiation (Eaton, 1931; Dunnam, 1943; Dale, 1959; Ehlig, 1969; Evenson, 1969; Wilson, 1972; Malik *et al.*, 1981; Kletter and Wallach; 1982). The removal of early fruiting forms reduces the number of assimilate sinks and allows the continuation of vegetative development or as concluded by Eaton (1931), when the nutritional dominance of bolls or fruit is removed, terminal bud and branch development is able to continue. The increased vegetative growth is characterised by an increase in the number of monopodial branches produced per plant (Dale, 1959; Evenson, 1969), increased plant height via increased internode length (Ehlig, 1969) and increased number of main-stem nodes (Malik *et al.*, 1981). When simulated damage includes tipping out of the main stem of plants, the number of monopodia initiated is increased significantly (Dale, 1959). Hence, the overall effect is to produce a larger plant of a greater dry weight than undamaged plants.

Increased square production is found to be highly correlated with increased vegetative growth following early defloration or disbudding (Eaton, 1931; Dunnam, 1943; Dale, 1959; Ehlig, 1969; Evenson, 1969; Wilson, 1972; Malik *et al.*, 1981; Kletter and Wallach; 1982), with increased secondary fruiting forms developing on sympodial and monopodial branches following disbudding (Dale, 1959). Increased squaring is dependent of the timing of the fruit removal in respect to the stage of growth of the plant. Dale (1959) found that bud formation declined once plants were allowed to start to set bolls. Similarly, Patterson *et al.*, (1978) found that the presence of a boll load dampened the flowering response to square removal and hence, square removal in more mature crops saw a decreased response in terms of square initiation.

Reports on the yield response to removal of fruiting forms are variable. Early fruit removal was found to increase yields (Eaton, 1931; Hamner,1941 cited by Dunnam *et al.*, 1943; Passlow and Trudgian,1960; Mistric and Covington, 1968). Reports of yield decreases with early fruit removal relate to situations where recovery was cut short by water deficit in the case of rain grown cotton (Dunnam *et al.*, 1943; Evenson, 1969) or temperature restrictions imposed on regrowth in short-season areas or when damaging a later fruiting type cotton (Kincade *et al.*, 1970). Dale (1959), Brown (1965), Dunnam *et al.*, (1943) and Passlow and Trudgian (1960) found yield decreases with later season defloration. Yield decreases are recorded with later season fruit removal. The presence of a boll load is found to dampen the vegetative regrowth of cotton following fruit removal (Ehlig and LeMert, 1973; Unger, Kletter and Wallach, 1987; Patterson *et al.*, 1978; Wilson and Bishop, 1982).

Increased boll weight in the bolls remaining is recorded following later season boll removal (Mistric and Covington, 1968). Matthews (1979) as cited by Peoples and Matthews (1981) report that shedding/removal of first position fruit on a fruiting limb increased the tendency for boll at second positions to be retained and produce significantly more seed cotton than where the first position fruit was intact. Developing bolls receive assimilates from bracts and leaves subtending the boll and sympodium (Ashley, 1972), and when bolls are removed from a fruiting position on a limb, assimilates are redistributed, first to other developing fruit forms on the same limb and then basipetally within the plant (Kerby *et al.*, 1987; Peoples and Matthews, 1981). Hence, when fruit remain on a fruiting branch or plant following fruit removal or damage, there is a tendency for the boll weight and seed cotton of the remaining bolls to increase and a decreased tendency for renewed vegetative growth as assimilates are channelled to the remaining bolls and lower plant parts rather than to vegetative growing points.

Delays in crop development are found to be associated with early defloration and the related increased vegetative growth and increased square production (Wilson, 1972; Ehlig and Le Mert, 1973; Bishop *et al.*, 1977; Wilson and Bishop, 1982; Kletter and Wallach, 1982; Unger *et al.*, 1987). It is suggested that delayed crop development may explain the yield decreases found by the various workers following defloration, where water deficit or climatic restrictions reduced recovery.

Evenson (1969) working in the Ord Valley of north west Australia, found delayed maturity but no yield differences following defloration up to 90 days into squaring, as the climate did not restrict crop development and all treatments were allowed to complete their development cycle. Similarly, Wilson (1972) used a 'determinate type ' cotton variety (i.e. a cotton variety which stops fruiting once the crop is set) in a sub tropical environment to delay the start of crop set by delaying the start of the insecticide program. No bolls were set until the spray program was initiated, vegetative plant development continued and hence the number of fruiting sites were increased. With the initiation of the spray program, bolls were allowed to set after which, production of new squares declined. The larger plants rapidly produced a larger number of fruiting sites and were able to recover yield and with no climatic restrictions to recovery, no yield differences were measured.

Passlow and Trudgian (1960) concluded that the maturity of the new squares depended on the length of growing season and growing conditions following damage. Under good growing conditions replacement of fruit forms will occur and increased yields can be attained but with adverse weather conditions following damage recovery may be prevented. Similarly, Dale (1959) concluded that the length of time disbudding can be continued without affecting yield depends on length of time available without environmental stress.

Wallach, (1980) and Kletter and Wallach (1982) conclude that a cotton crop responds to removal of fruiting forms in different ways; including increased vegetative growth, increased production of squares, increased flowering and boll weight. The result being that fruiting body removal does not always decrease yield, although yield is delayed where compensation is occurring.

Kletter and Wallach (1982) and Unger, Kletter and Wallach (1987) studied the fruiting patterns of cotton following removal of various fruiting forms and found square and boll development times as defined in thermal time were constant following a range of disfloration treatments. They suggest that the compensatory pathway can be explained in terms of replacement of natural shedding and the effects of changes in boll load.

Unger *et al.* (1987) initially found that following square removal, flowering was reduced and then followed by a period of increased squaring and flowering with a delay observed between the two cycles. As the crop approached cut out, square removal did not affect fruiting as the squares removed were destined for natural shedding. Increased squaring following early square removal correlated with increased vegetative growth and increased dry matter production. But there was a reduced response in terms of vegetative growth and increased flowering with damage inflicted mid-season (i.e. plants near cut out) and late-season. Early small boll removal similarly increased total flowering, but mid- and late- small boll removal increased flowering to lesser extents. Boll opening was found to follow the same delayed pattern. Removal of small bolls at early boll opening led to retaining of other bolls, some of which would have been naturally shed. Removal of large bolls always decreased yield but induced more small bolls to be retained. Compensation for removal of large bolls late in the season was enhanced when boll set was delayed as a result of early square removal and hence full boll load was yet to be attained, i.e. cut out had been delayed.

Hence, in cotton, the compensation response for fruit damage or removal is characterised by increased vegetative growth, increased production of squares, increased flowering and boll weight; and the pathway of compensation for removal of fruiting forms is explained in terms of replacement of natural shedding and the effects of changes in boll load on the crop (Unger, Kletter and Wallach, 1987).

Hearn and Room (1979) in reviewing studies on compensatory growth in cotton define four types of damage responses of cotton to insect attack:-

1. Instantaneous Tolerance - which occurs when fruit are damaged that would have naturally shed and hence no change is produced in the fruiting pattern of the crop.

2. Time Dependent Tolerance - which occurs when squares or bolls that would have shed physiologically replace those previously damaged, resulting in delayed boll setting but no increase in the number of fruiting sites.

3. Instantaneous Compensation - occurs when materials or assimilates that would have been allocated to damaged bolls are reallocated to undamaged bolls, resulting in larger bolls and no delay in fruit setting nor increase in number of fruiting sites.

4. Time Dependent Compensation - occurs when loss of fruit delays metabolic stress thus prolonging vegetative growth and square production and allowing additional squares to set as bolls. In this case boll setting is delayed and the number of fruiting sites are increased.

The pathways of plant compensation for damage in cotton (Hearn and Room, 1979; Kletter and Wallach, 1982) are illustrated in the range of work carried out simulating insect damage to cotton crops.

A limited number of studies have looked at differences in the varietal responses to simulated insect damage. Eaton (1931) suggested that more 'determinate' cotton types should respond more to defloration, in that the removal of fruiting forms would allow the variety to restart vegetative growth where the more indeterminate types would maintain some vegetative growth with or without defloration and show a decreased response. Patterson *et al.*, (1978) found that limiting boll set in the early season induced an greater increase in rate of flower production in more determinate varieties.

Brown (1965) found site and varietal differences in responses to damage with removal of early squares inducing increased square production and boll numbers in all varieties tested. But later removal only saw increased square production in two of the three varieties and in a short season area, yield decreases were measured for the third variety. He concluded that the third variety normally produces a higher percentage of its flowers early in the season and hence, removal of all squares in the first period saw a larger proportion of total squares removed in this variety and it did not increase the number of squares produced after the damage to sufficiently compensate for the loss. Siokra 1-4, an early and rapid fruiting variety, is reported to compensate for early fruit removal to a greater extent than the longer season variety, Deltapine 90, in insect control trials carried out by Brook *et al.*, (1993a, b, c). It is suggested that the fruiting pattern of a cotton variety combined with its maturity type contribute to its ability to compensate for fruit removal under given climatic conditions.

Chapter 3

Materials and Methods

3.1 Experimental Site

The experiments described in this work were carried out at the Australian Cotton Research Institute, Narrabri, New South Wales, Australia (149^0 47' E, 30^0 13' S) during the 1991-92 and 1992-93 cotton seasons. The area is generally considered to be a semi-arid climate but variable within and between years. Summer or crop season rainfall varies from 100 to 600 mm. While maximum temperatures rise above 40 ^{0}C in mid summer, the average maximum temperature is 33 ^{0}C with an average minimum summer temperature of 19 ^{0}C. Average maximum and minimum winter temperatures are 17 ^{0}C and 4 ^{0}C, respectively.

The soil type at the experimental site is typical for the area being a grey cracking clay (Vertisol or Typic Pellustert), classified as Ug 5.2 by Northcote *et al.* (1975). It is a fine textured soil (60% clay, 20% silt and 20% sand), strongly structured with a uniform profile predominantly of smooth faced peds. It has high shrink and swelling characteristics and cracks significantly when dry. A self mulching surface layer is sticky when wet but when dry forms a loose layer of granular to fine polyhedral aggregates. Heavy rain penetrates deeply down cracks in dry soil but once the surface wets and swells, further infiltration is very slow. Saturated conductivity has been measured at approximately 1 mmd^{-1} (Mason *et al.*, 1980 cited by Constable and Rochester, 1988). The soil is relatively fertile with only nitrogen fertiliser needed. The pH in water is 8.2 (Constable and Rochester, 1988).

Cotton (*Gossypium hirsutum* L.) was sown on one metre beds in early October and furrow irrigated as required. Crop management in terms of fertilisation, irrigation and insect control was carried out according to the standard commercial practice for the area and is summarised in Appendix 3.1. The crops were mature for commercial picking in late May in 1991/92 and late April in 1992/93.

3.2 Cotton Varieties

Deltapine Acala 90 and Siokra 1-4 cotton cultivars (*Gossypium hirsutum* L.) were selected. Deltapine Acala 90, more commonly known as Deltapine 90, is a cultivar bred by the Delta and Pine Land Company of the U. S. A. It is of Acala heritage and as the hail damage loss assessment method is based on Acala type cotton varieties, it was selected as the hail assessment standard. It was the predominant cultivar grown in Australian cotton production areas until the introduction of C. S. I. R. O. varieties in 1984. Deltapine 90 continues to be grown in significant areas. Deltapine 90 is a long season or late maturing determinate cultivar with broad (i.e. normal) leaf type, an erect growth habit and semi-cluster fruiting (Gilbert, 1985).

Siokra 1- 4, a cotton cultivar developed by the C. S. I. R. O., is currently recognised as the Australian cotton industry standard cultivar and was used as a comparison to Deltapine 90. Siokra 1-4 is a high yielding, okra leaf cultivar, earlier in maturity than Deltapine 90 by up to 7 days, with resistance to Bacterial Blight (*Xanthomonas campestris*) (Thomson, 1986). The okra leaf trait is characterised by deeply cleft and narrowly lobed leaves with less surface area per leaf than normal leaf cotton (Figure 3.2.1), providing a more open canopy type. The okra leaf character is associated with early maturity, manifested in a rapid flowering rate and a greater production of squares and bolls of which a large number are shed (Andries *et al.*, 1969; Thomson, 1985; Thomson, 1986).

The Siokra cultivars were developed from a complex cross between a Deltapine 61 derived line containing various mutant genes including okra leaf type, and Namcala crossed with Tamcot SP37 cotton (Thomson, 1986). Deltapine 61 was a high yielding Arizonan cultivar and was the predominant variety grown in Australia from 1979 to 1985. Namcala bred in New Mexico, was a high quality but low yielding cultivar, grown commercially on a small scale in Australia up to 1985. Resistance to Bacterial Blight (*Xanthomonas campestris*), which can cause significant losses in Australia, was conferred by crossing with Tamcot SP37 is a short season (early maturing) Texan variety with major genes for resistance to Bacterial Blight. Intensive selection produced an okra leaf cultivar, of erect plant habit, resistance to Bacterial Blight, high yielding and with good lint quality (Thomson, 1986).

Figure 3.2.1: Diagrammatic Representation of Cotton (*Gossypium hirsutum* L.) Leaf Types Used in These Studies.
Source: Adapted from Thomson (1971).

Normal Leaf genotype

Okra leaf genotype

3.3 Experimental Design

Experiments were designed as Nearest Neighbour designs with four replications. Two levels of simulated hail damage (Zero and Moderate) were inflicted on the two cotton cultivars at four separate growth stages (V3, V5, R8 and R12+) according to the growth stages of Elsner *et al.* (1979). Subsequent statistical analysis showed that in-field variation was minimal and that the Randomised Complete Block model held, and data were analysed as such.

Plot size was five metres by five metres (i.e. five metres long by five rows wide). Hail damage simulations were carried out over the entire plot area, enabling sample rows to be buffered by similarly treated cotton.

3.4 Damage Simulation Techniques

Symptoms of hail injury include stand reduction, defoliation and stem cut off or bruising, inflorescence damage, fruit damage or removal. When the crop is in the vegetative stages, losses are the result of firstly stand reduction and secondly, by plant cut-off and defoliation. Severe plant damage inflicted by hail stones at or below cotyledon level will cause immediate plant death as no leaf meristem is present below this point. Hence, the result of such damage is stand reduction. Where plants are severely bruised or incur main stem cut-off above the cotyledon level and are defoliated, new vegetative branches and vegetative material must be initiated from meristems in leaf axils at undamaged nodes. Damage in the reproductive stages not only includes main stem damage and defoliation but also fruiting branch damage or removal and fruit damage or removal.

The aim of the hail damage simulation was to reproduce these symptoms as accurately as possible. In these experiments, hail damage was simulated at the V3, V5, R8 and R12+ growth stages, as defined by Elsner *et al.* (1979). Examples of cotton plants at these growth stages are depicted in Figures 3.4.1 - 3.4.4.

Hail damage was simulated at dates relating to growth stage according to Table 3.4.1.

Table 3.4.1 Damage Simulation Dates defined in Growing Day Degrees from Planting.

Treatment (Growth Stage at Time of Damage)	Damage Date from Planting (Growing Day Degrees)	Damage Date from Planting (Growing Day Degrees)
	1991/92	**1992/93**
V3	203	190
V5	506	337
R8	1129	916
R12+	1718	1305

Damage in the V3 and V5 stages was inflicted using secateurs to impose main stem cut off. Cut off below the cotyledons was used to cause stand reduction and cut off immediately below the first vegetative node simulated non-fatal main stem cut off by a hail stone (i.e. causing plant damage and not plant death). Cotyledons and leaf material were removed by hand to simulate defoliation.

Hail damage was simulated at the R8 and R12+ stages by a combination of methods. Main stem cut off and fruiting branch removal being inflicted using secateurs. Random removal of foliage and lower fruit was inflicted using a garden rake.

A moderate level of simulated damage (50 - 60 %) was selected as the treatment level for simulated damage to be inflicted at each of the selected growth stages. From the U. S. A. National Crop Insurance Service (N. C. I. S.) assessment procedures, damage to the plant structure as outlined in Tables 3.4.2 and 3.4.3 produces an assessed damage level of 50 - 60 % at the defined growth stages. Damage was inflicted according to these levels at each of the V3, V5, R8 and R12+ growth stages in each experiment.

Table 3.4.2: Hail Damage Simulation - Vegetative Growth Stages Treatments

Vegetative Stage Hail Damage Simulation Treatments			
Growth Stage	**Main Stem Cut-off**		**Defoliation**
	Level of Cut-off	Percentage of Plants with Cut-off	
V3	Below cotyledon node	80	100
	Below node 1 (CC)	20	
	Below node 2 (C1)	0	
V5	Below cotyledon node	50	100
	Below node 1 (CC)	40	
	Below node 2 (C1)	10	

Table 3.4.3: Hail Damage Simulation - Reproductive Growth Stages Treatments

Reproductive Stage Hail Damage Simulation Treatments					
Growth Stage	**Main Stem Cut-off**		**Fruiting Limbs Removed**	**Fruit Removed**	**Defoliation**
	Level of Cut-off	Percentage of Plants with Cut-off			
R8	C10	100	2 Limbs/plant	1.5 Large Bolls plant	Approx. 30%
R12+	C13	100	2 Limbs/plant	1.5 Large Bolls per plant	Approx. 30%

Figure 3.4.1: **Cotton Growth Stage - V3**
(Adapted from "Australian Cotton Industry Cotton Loss Instructions Manual", Robins-M. B. S., 1987).

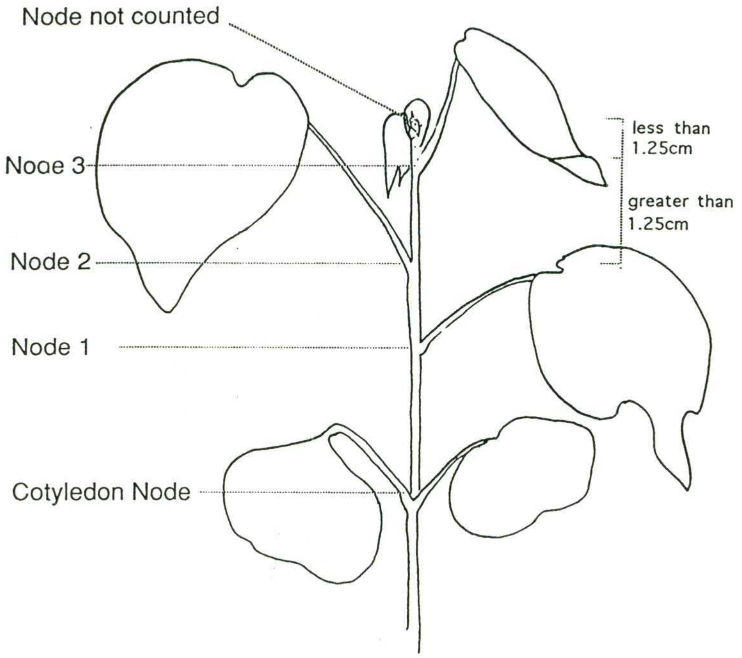


Figure 3.4.2: **Cotton Growth Stage - V5**
(Adapted from "Australian Cotton Industry Cotton Loss Instructions Manual", Robins-M. B. S., 1987).

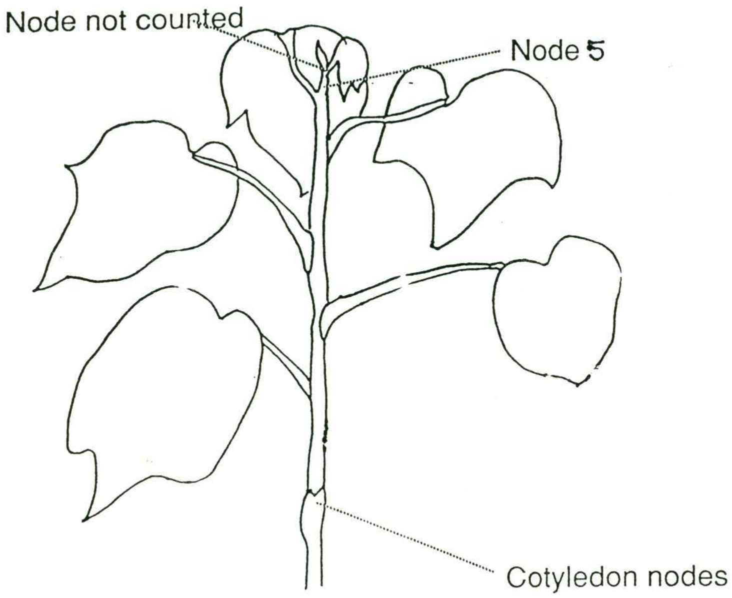


Figure 3.4.3: **Cotton Growth Stage - R8**
(Adapted from "Australian Cotton Industry Cotton Loss Instructions Manual", Robins-M. B. S., 1987).

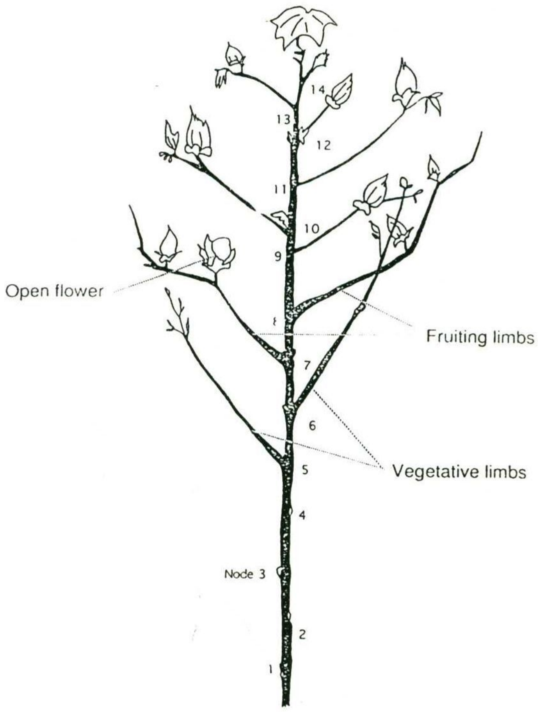
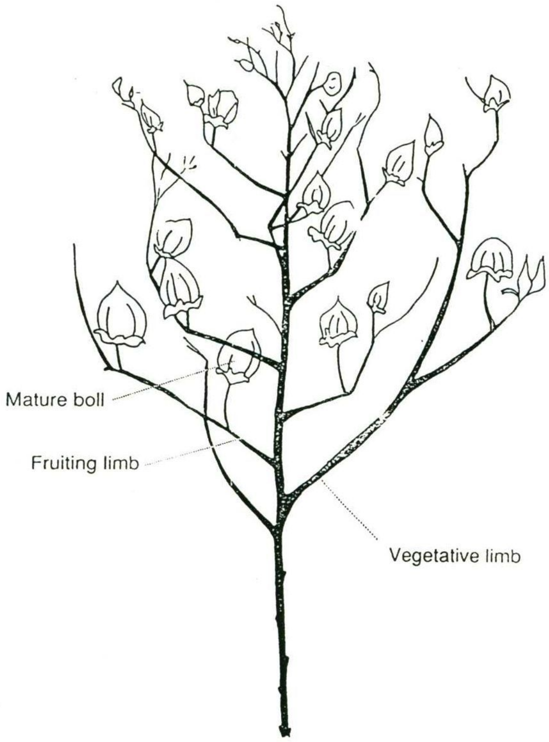


Figure 3.4.4: **Cotton Growth Stage - R12+**
(Adapted from "Australian Cotton Industry Cotton Loss Instructions Manual", Robins-M. B. S., 1987).



3.5 Assessment of Hail Damage

Assessment of losses to cotton crops due to hail damage in Australia is made using the loss assessment procedures developed by the U. S. National Crop Insurance Service. They are based on Acala type lines of which the Deltapine lines are representative. These procedures have been in use in Australia for about 15 years. Commercial assessment of hail damage is carried out 14 days after the hail strike so that the full extent of plant material loss is evident and included in the loss assessment. In keeping with commercial practice, assessment of the level of simulated hail damage inflicted in damage simulations was carried out 14 days after the simulations were carried out.

The loss of plant parts by direct cut off of the stem or removal of fruit is immediately evident following a storm. Not immediately evident is the effect of bruising injuries which take a period of time to set in and may ultimately result in death or loss of the damaged plant part. Bruising injuries are exacerbated by the adverse weather conditions (eg. wet or humid conditions) following the hail strike i.e. growth of tissue and healing of wounds is impaired. This is evident in these experiments where damage was inflicted to produce an assessed level of damage of 50 - 60 % but assessed damage 14 days after the damage simulation saw assessed damage levels being increased in some cases (Table 3.5.1).

Table 3.5.1: Comparison of Inflicted and Assessed Simulated Damage Levels

	Experiment 1991/92		Experiment 1992/93	
Growth Stage	**Average Damage Level Inflicted[1] %**	**Assessed Damage Level[2] %**	**Average Damage Level Inflicted[1] %**	**Assessed Damage Level[2] %**
V3	51	60	51	71
V5	55	58	55	45
R8	55	46	55	60
R12	60	72	60	64

[1] Damage Inflicted = Damage level inflicted in simulation according to calculations in Tables 3.4.2, 3.4.3

[2] Assessed Damage Level = Level of damage as assessed by N. C. I. S. procedures 14 days after damage.

3.6 Climatic Patterns 1991/92 and 1992/93

Weather data relating to all experiments were collected at the Australian Cotton Research Institute, Narrabri. Data covering the period are presented in Figures 3.6.1-3.6.4 and Tables 3.6.1 and 3.6.2.

Temperatures were average to slightly above average for each month during the 1991/92 season and hence, growing day degree accumulation was above the long term average for the corresponding periods. After a warm and dry start to the season and good stand establishment, heavy rain occurred in December during peak squaring and then again in February during late squaring/boll filling. Leaf development and square retention were adversely affected by these periods of overcast weather. January was a period of warm clear weather and rapid reproductive development was observed during this period. The short boll setting period resulted in a short and rapid boll opening period.

The 1992/93 season began with a lower than average temperatures and growing day degree accumulation and resulted in slow plant stand establishment. This is reflected in the slow crop regrowth following vegetative stage hail simulations. From January conditions improved, with little rain and warm temperatures experienced for the remaining part of the season. Although temperatures and relative humidity averaged over January and February were not extraordinarily high, two three weeks of very temperatures and high humidity were recorded. A dry April allowed for good picking conditions.

Figure 3.6.1: Day Degree Accumulation for 1991/92 Cotton Season

Site: Australian Cotton Research Institute, Narrabri, Australia.

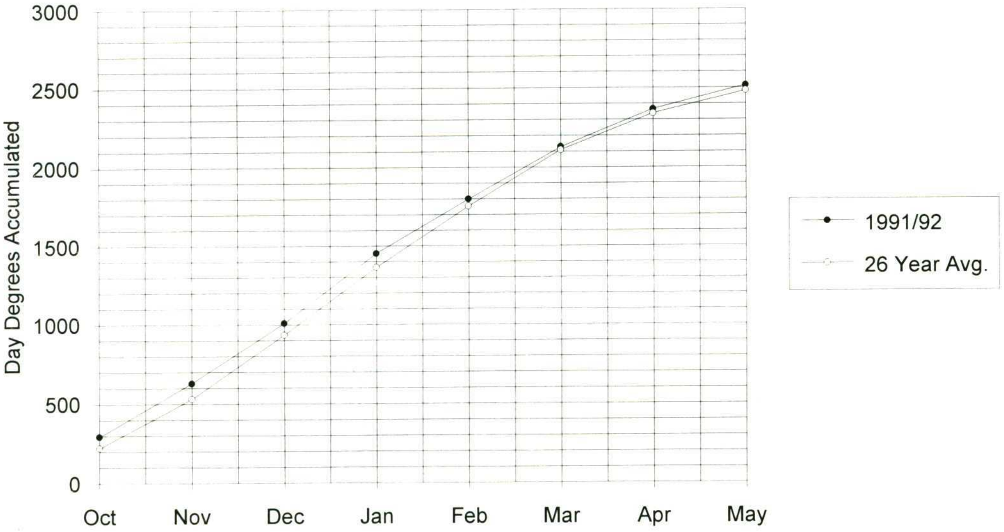


Figure 3.6.2: Rainfall for 1991/92 Cotton Season

Site: Australian Cotton Research Institute, Narrabri, Australia.

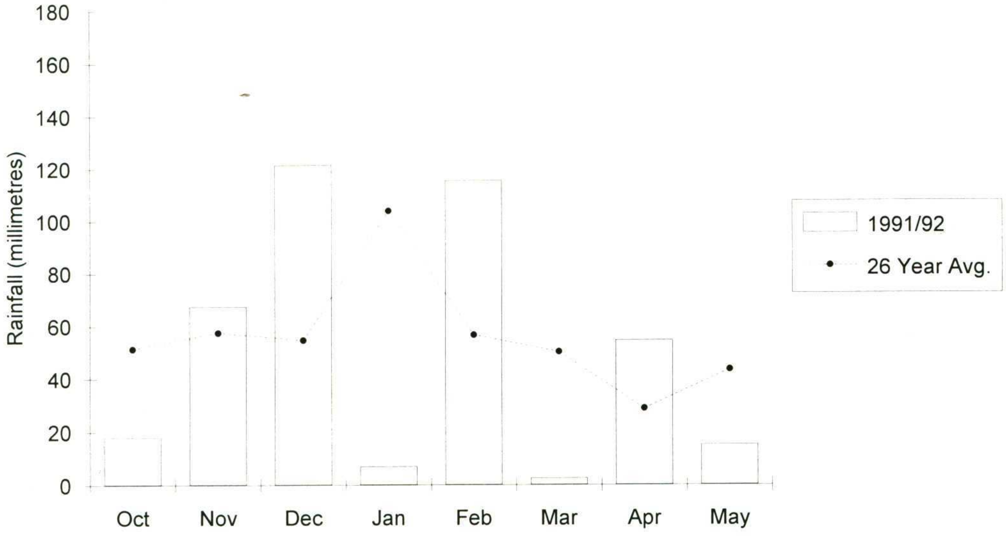


Figure 3.6.3: **Day Degree Accumulation for 1992/93 Cotton Season**
Site: Australian Cotton Research Institute, Narrabri, Australia.

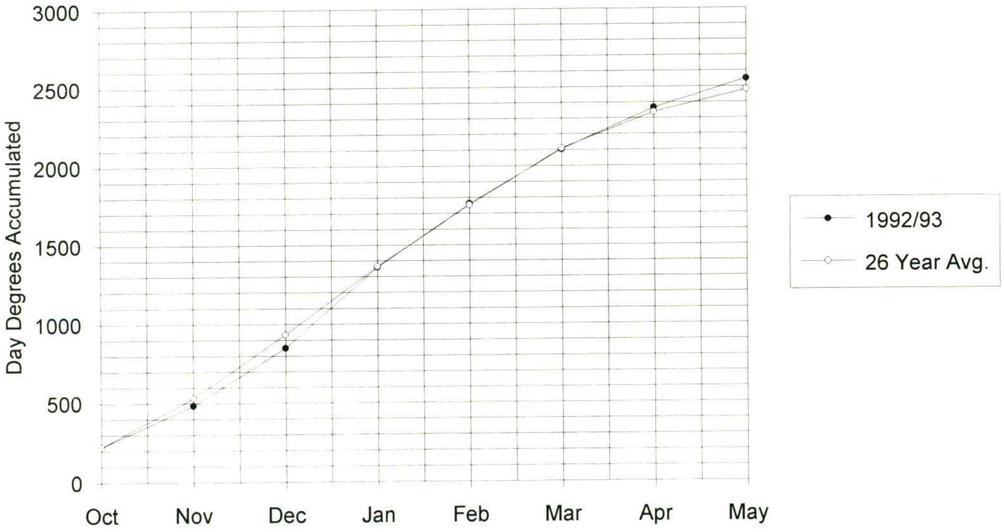


Figure 3.6.4: **Rainfall for 1992/93 Cotton Season**
Site: Australian Cotton Research Institute, Narrabri, Australia.

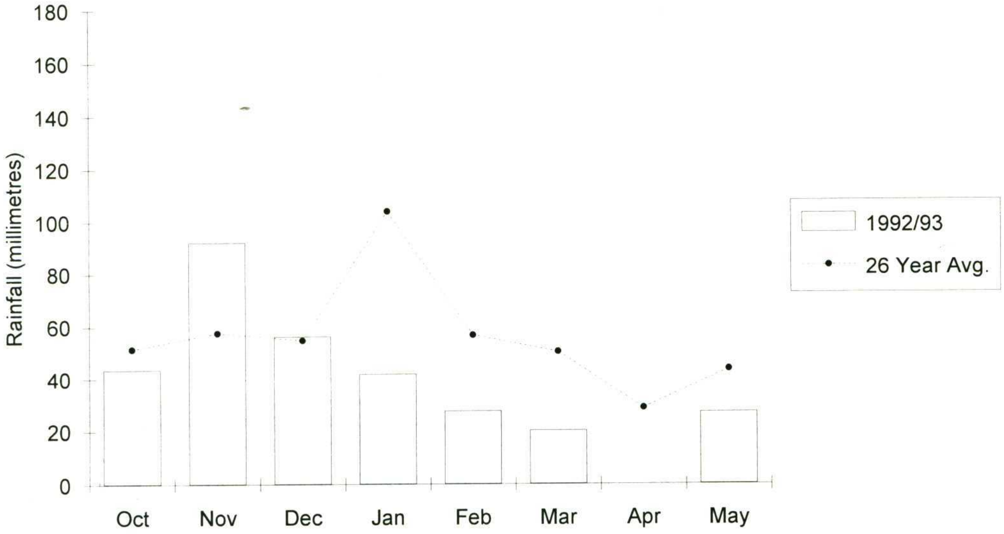


Table 3.6.1: Summary of Weather Data for Cotton Season 1991/92

Month	Rainfall (mm)	Maximum Temperature (^{0}C)	Minimum Temperature (^{0}C)	Radiation (Langley)	Soil Temperature (^{0}C)	Relative Humidity (%)	Growing Day Degrees	Accumulated Growing Day Degrees
Oct	18 (51.4)	29.2 (25.9)	13.2 (12)	534 (493)	16.4 (17.6)	44 (57)	294 (223)	294 (223)
Nov	67.4 (57.5)	30.1 (29.5)	16.3 (15.1)	547 (570)	18.7 (21.3)	48 (53)	336 (308)	630 (531)
Dec	121.4 (54.7)	30.9 (32.2)	17.5 (17.8)	593 (605)	19.9 (24.4)	47 (54)	378 (403)	1008 (934)
Jan	7 (103.9)	34 (32.5)	18.7 (19.2)	617 (590)	21.7 (25.6)	45 (60)	445 (430)	1453 (1364)
Feb	115.4 (56.6)	30.4 (32.5)	17.4 (19.3)	495 (547)	20.7 (25.5)	63 (63)	345 (390)	1798 (1754)
Mar	2.6 (50.2)	30.9 (30.1)	14.1 (16.8)	510 (484)	19 (23.2)	59 (62)	331 (355)	2129 (2109)
Apr	54.6 (28.7)	26.9 (26.4)	11.3 (12.2)	359 (380)	15 (18.8)	65 (63)	235 (228)	2364 (2337)
May	15.2 (43.5)	21.6 (21.2)	8.2 (7.9)	271 (278)	10.6 (14.1)	67 (70)	149 (142)	2513 (2479)
	Total	Avg.	Avg.	Total	Avg.	Avg.	Total	
	401.6 (446.5)	29.25 (28.7)	14.588 (15)	3926 (3947)	17.75 (21.3)	54.8 (60.3)	2513 (2479)	

* In brackets is presented the 26 year average.

Table 3.6.2: **Summary of Weather Data for Cotton Season 1992/93**

Month	Rainfall (mm)	Maximum Temperature (^{0}C)	Minimum Temperature (^{0}C)	Radiation (Langley)	Soil Temperature (^{0}C)	Relative Humidity (%)	Growing Day Degrees	Accumulated Growing Day Degrees
Oct	43.5 (51.4)	25.3 (25.9)	10.7 (12)	496 (493)	16.4 (17.6)	54 (57)	223 (223)	223 (223)
Nov	92.1 (57.5)	27 (29.5)	13.6 (15.1)	551 (570)	19.4 (21.3)	52 (53)	261 (308)	484 (531)
Dec	56.2 (54.7)	29.9 (32.2)	17.7 (17.8)	553 (605)	21.5 (24.4)	58 (54)	366 (403)	850 (934)
Jan	41.7 (103.9)	35.3 (32.5)	21.6 (19.2)	618 (590)	23 (25.6)	65 (60)	510 (430)	1360 (1364)
Feb	27.6 (56.6)	33.3 (32.5)	19.3 (19.3)	574 (547)	22.3 (25.5)	65 (63)	402 (390)	1762 (1754)
Mar	20.1 (50.2)	29.9 (30.1)	15.8 (16.8)	507 (484)	20.4 (23.2)	63 (62)	341 (355)	2103 (2109)
Apr	0 (28.7)	28.4 (26.4)	12.2 (12.2)	384 (380)	15.4 (18.8)	56 (63)	262 (228)	2365 (2337)
May	27 (43.5)	23.2 (21.2)	9.5 (7.9)	276 (278)	13.2 (14.1)	69 (70)	184 (142)	2549 (2479)
	Total 308.2 (446.5)	Avg. 29.038 (28.7)	Avg. 15.05 (15)	Total 3959 (3947)	Avg. 18.95 (21.3)	Avg. 60.3 (60.3)	Total 2549 (2479)	

* In brackets is presented the 26 Year Average

Chapter 4

Plant Height Development in Cotton Varieties after Damage by Simulated Hail

4.1: Introduction

The vegetative development of the cotton plant can be characterised by monitoring either average plant height or the leaf area index of the crop. Initially, plant height development in cotton is exponential, as the main stem elongates rapidly up to the start of the flowering period (Heath, 1937). The indeterminate growth habit of cotton means that as flowering begins, fruiting branch and fruit development occur concurrently with plant height development (Mauney, 1986). As reproductive development competes with vegetative development for carbohydrate supply, height development diverges from the exponential to form a sigmoid pattern (Marani and Ephrath, 1985). This pattern of development for dry matter production is similar to the development pattern for leaf area index and fruit set (Stern, 1965).

Cotton cultivars are found to differ in growth and fruiting patterns (Gilbert, 1985; Thomson, 1986; Wells and Milroy, 1994). By incorporating the okra leaf characteristic into C. S. I. R. O. bred lines such as Siokra 1-4, breeders have conferred decreased plant height and vegetative branch number, increased rate of fruiting and earlier crop maturity compared to the Acala type lines such as Deltapine 90 (Thomson, 1985). Varietal differences in the rate of regrowth after hail damage have been observed in commercial cotton crops in Australia (Cotton Research and Development Corporation, 1990, unpublished). The aim of this study was to identify differences in plant height development in cotton varieties after damage to the canopy by simulated hail.

4.2: Methods

Experiments were carried out at the Australian Cotton Research Institute, Narrabri, Australia (149^0 47' E, 30^0 13' S) during the 1991/92 and 1992/93 cotton seasons examining the regrowth of cotton varieties after simulated hail damage as described in Chapter 3. Hail damage was simulated at four plant growth stages during the season as described previously. Average plant height was monitored on one metre square sample areas at 7-10 day intervals.

4.3: Results and Discussion

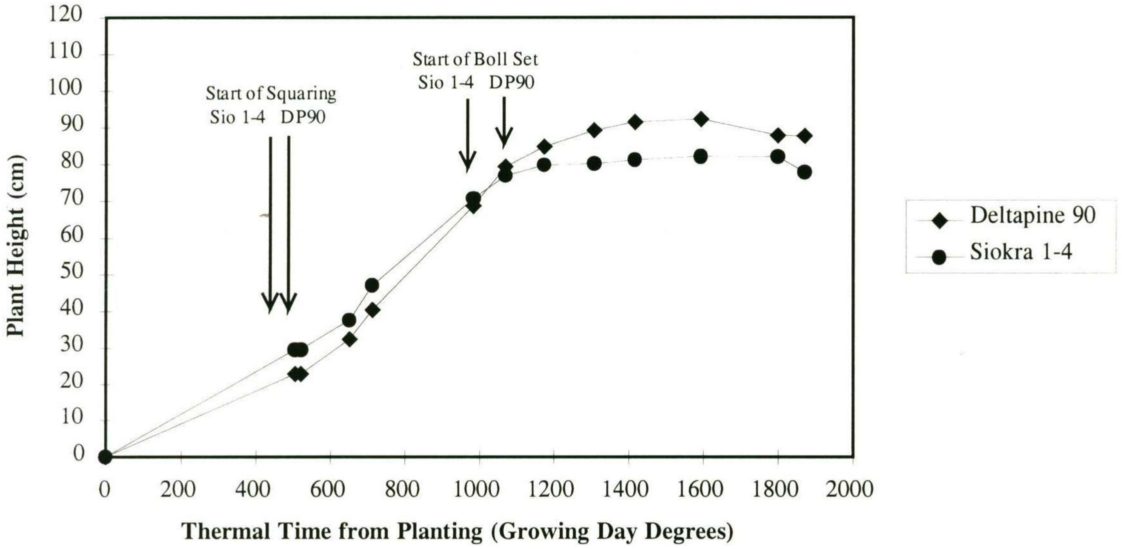
Plant Height Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars.

In undamaged cotton, the initial vegetative development of Siokra 1-4, in terms of plant height development, was more rapid than in Deltapine 90. Throughout stand establishment and the squaring phase the height advantage of Siokra 1-4 over Deltapine 90 was highly significant ($P < 0.001$) (Figures 4.3.1 and 4.3.2).

In 1991/92, Siokra 1-4 initiated squaring at approximately 440 Growing Day Degrees (GDD) from planting, slightly ahead of Deltapine 90 at approximately 500 GDD. As Siokra 1-4 moved into the boll setting phase, its rate of vegetative development slowed and hence its rate of increase in plant height slowed and finally reached a plateau (Figure 4.3.1).

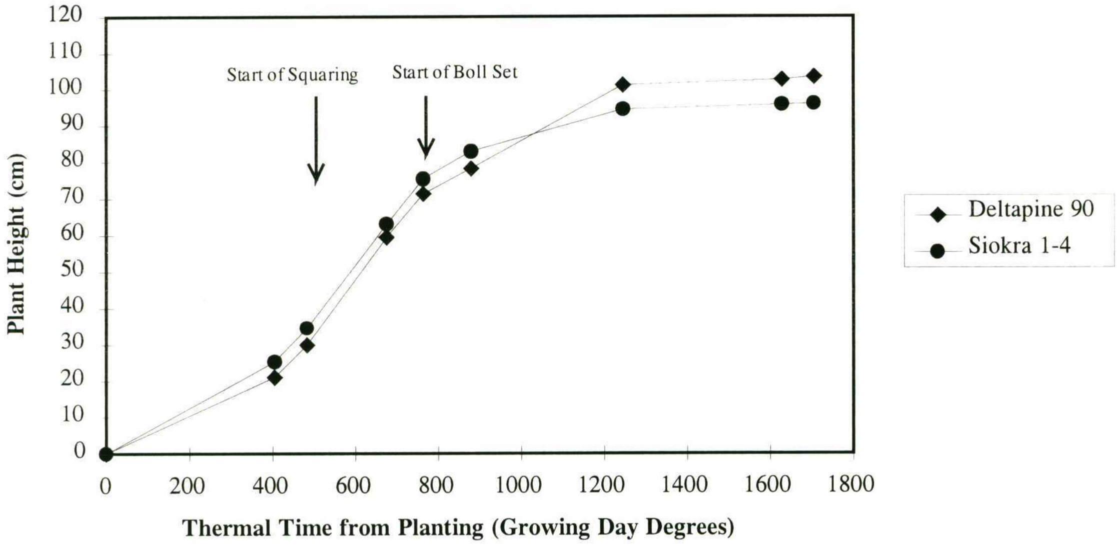
Deltapine 90 entered its boll setting phase at approximately 1069 GDD, one sampling date later than Siokra 1-4 which had begun to set bolls by 983 GDD from planting. Deltapine 90 continued to grow vegetatively for this period of 80 GDD and ultimately produced a greater final plant height (Figure 4.3.1). This effect was repeated in 1992/93 (Figure 4.3.2). Although both cultivars began squaring and boll set at similar dates in the 1992/93 season. The initial rate of boll set in Deltapine 90 was slower than Siokra 1-4 and the rate of vegetative growth did not decrease for a period of approximately 200 GDD after the decline in rate of vegetative growth in Siokra 1-4. The growth pattern of both cultivars and in both seasons followed the sigmoid pattern described by Marani and Ephrath (1985).

Figure 4.3.1 Development of Plant Height in Deltapine 90 and Siokra 1-4 Cotton Cultivars (Site: Narrabri, 1991/92)



At 521 GDD, l.s.d.$_{(0.01)}$ = 5.71 cm
At 652 GDD, l.s.d.$_{(0.05)}$ = 2.77 cm
At 713 GDD, l.s.d.$_{(0.05)}$ = 4.08 cm
At 1307 GDD, l.s.d. $_{(0.01)}$ = 4.81 cm
At 1416 GDD, l.s.d. $_{(0.001)}$ = 9.81 cm
At 1595 GDD, l.s.d. $_{(0.01)}$ = 6.81 cm
Differences between cultivars at other sampling points are not significant.

Figure 4.3.2 **Development of Plant Height in Deltapine 90 and Siokra 1-4 Cotton Cultivars (Site: Narrabri, 1992/93)**



At 483 GDD, l.s.d.$_{(0.05)}$ = 1.42 cm
At 674 GDD, l.s.d.$_{(0.01)}$ = 1.35 cm
At 1245 GDD, l.s.d.$_{(0.001)}$ = 3.21 cm
At 1705 GDD, l.s.d.$_{(0.05)}$ = 3.43 cm
Differences between cultivars are not significant at other sampling points.

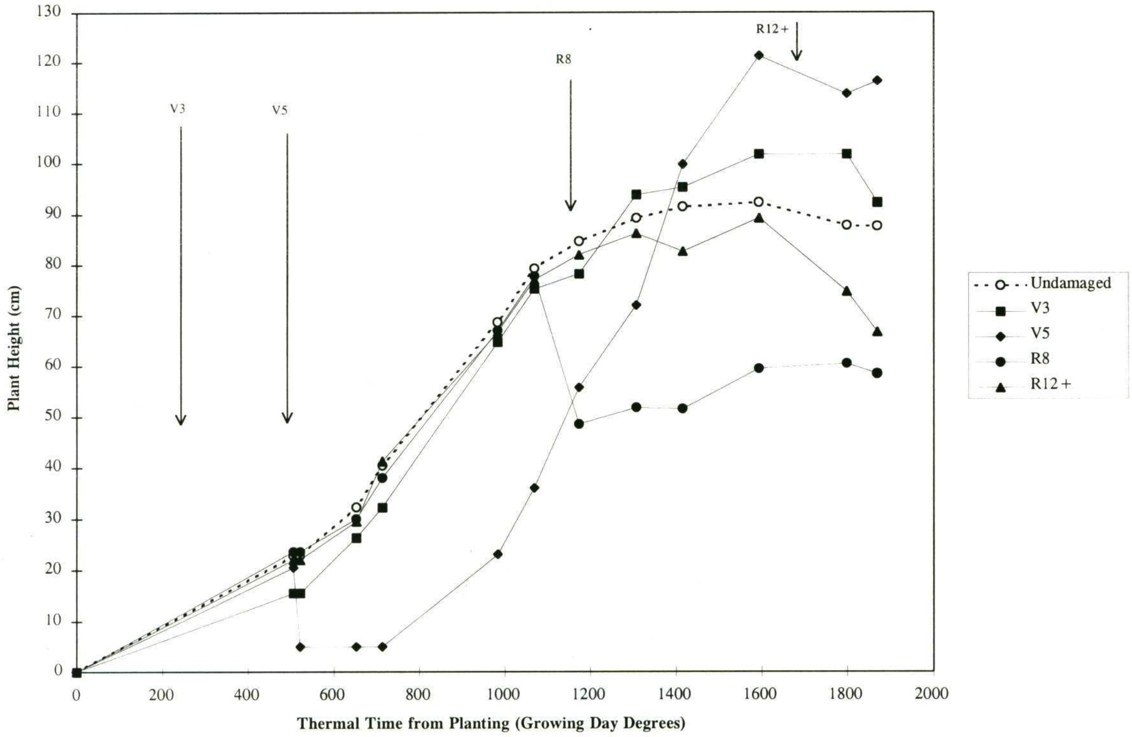
Plant Height Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage.

After simulation of hail damage at the vegetative growth stages of V3 and V5, no new vegetative plant material was visible for a period of 7-14 days following the damage (Figures 4.3.3 and 4.3.4). No increase in plant height ($P > 0.05$) was measured for a period of 180-200 GDD following the damage simulated at the V5 growth stage in 1991/92 in either cotton cultivar. This response was the same in Deltapine 90 but not in Siokra 1-4 in 1992/93 where good weather conditions following the damage simulations at the V3 and V5 growth stages were conducive to rapid vegetative growth, regrowth was quickly initiated and a reduced period of no growth was observed (Figures 4.3.5 and 4.3.6). Although no regrowth was measurable during this initial period following damage, it is suggested that this time was required for repair of tissue damaged by the damage simulation and for the initiation of new growth apices and the activation of growth in apices previously suppressed by apical dominance (Salisbury and Ross, 1992).

As a result of this period of no measurable growth, plant height development was delayed by hail damage simulation in the vegetative growth stages. The development curve shifted further into the growing season. Damage at the V3 growth stage delayed crop development an average of 158 GDD while damage at the V5 growth stage delayed development 327 GDD.

Actual hail damage (as compared to simulated hail damage) delays the maturity of crops by delaying development (soybeans, Fehr *et al.*, 1984; corn, Baldridge, 1976; corn, Hicks *et al.*, 1977; corn, Vasilas and Seif, 1985; Pinto beans, Baldridge, 1971; peas, Miller and Muelbauer, 1984; rapeseed, McGregor, 1987 and tobacco, Whitfield, 1982). Similarly, delayed maturity is associated with early defloration in insect damage simulation experiments on cotton (Wilson *et al.*, 1972; Ehlig and Le Mert, 1973; Bishop *et al.*, 1977; Wilson and Bishop, 1982; Kletter and Wallach, 1982; Unger *et al.*, 1987).

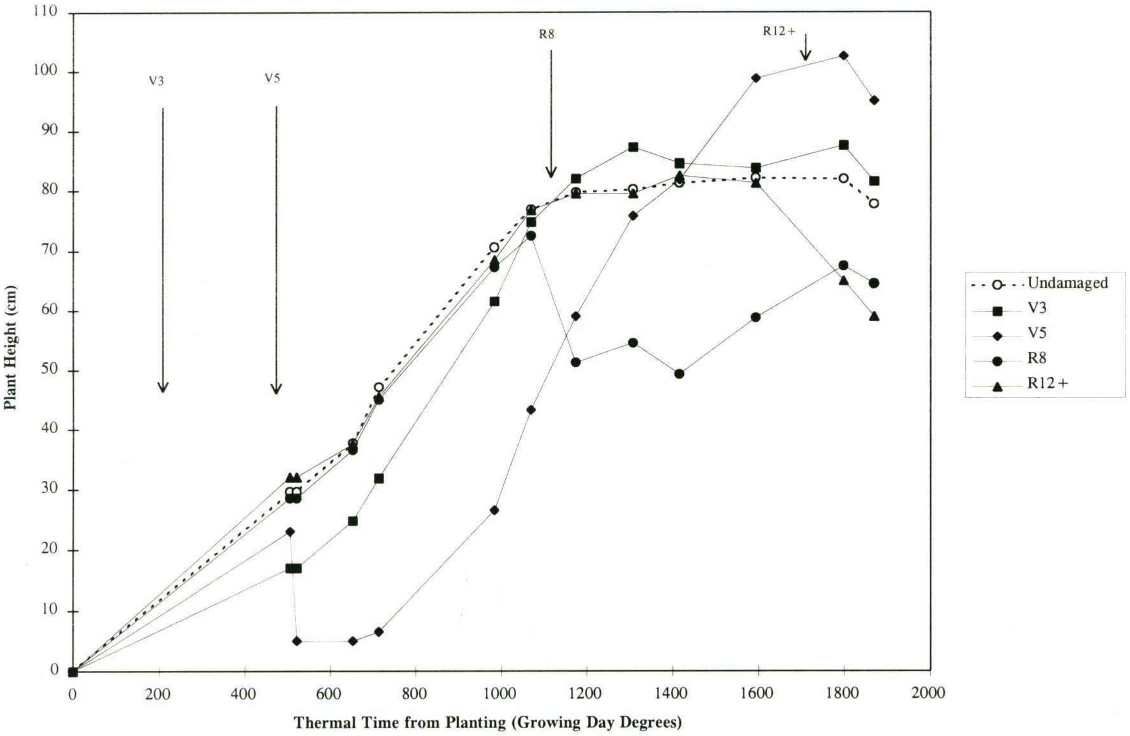
Figure 4.3.3 **Development of Plant Height in Deltapine 90 Cotton Following Simulated Hail Damage (Site: Narrabri, 1991/92)**
(Arrows indicate growth stage for simulated damage)



At 521 GDD, l.s.d.$_{(0.001)}$ = 5.33 cm
At 652 GDD, l.s.d.$_{(0.001)}$ = 3.14 cm
At 713 GDD, l.s.d.$_{(0.001)}$ = 3.49 cm
At 983 GDD, l.s.d.$_{(0.001)}$ = 6.50 cm
At 1069 GDD, l.s.d.$_{(0.001)}$ = 4.77 cm
At 1174 GDD, l.s.d.$_{(0.001)}$ = 8.70 cm
At 1308 GDD, l.s.d.$_{(0.001)}$ = 8.15 cm
At 1416 GDD, l.s.d.$_{(0.001)}$ = 10.17 cm
At 1594 GDD, l.s.d.$_{(0.001)}$ = 6.48 cm
At 1798 GDD, l.s.d.$_{(0.001)}$ = 12.47 cm

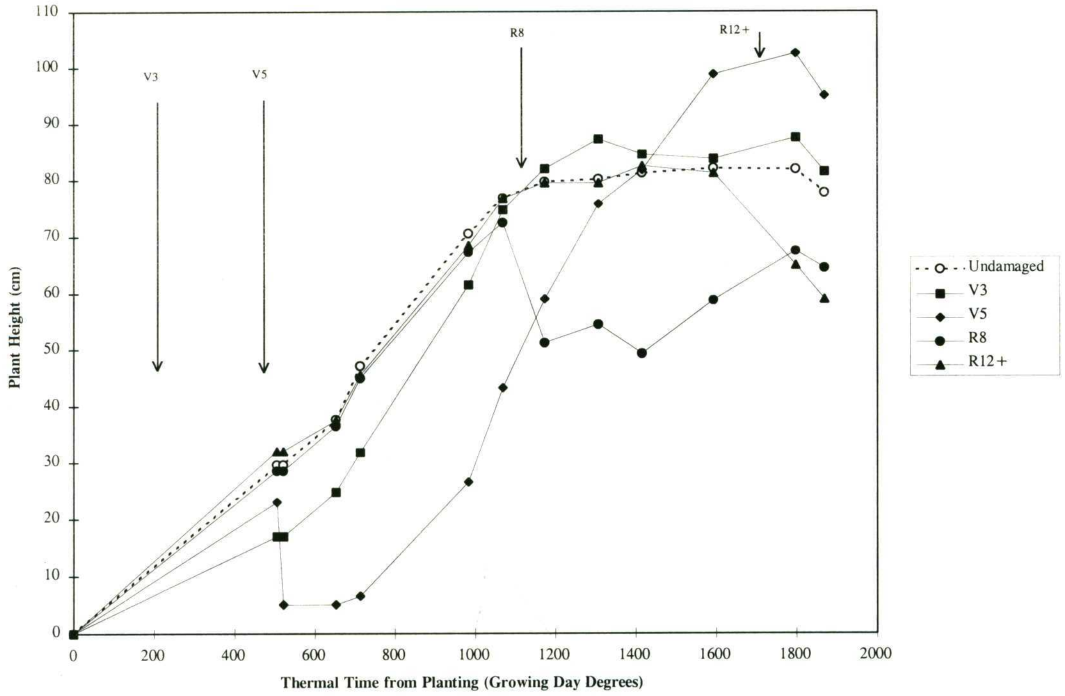
As the crop recovered from the damage in the vegetative growth stages and began to replace vegetative material, plant height increased in the typical sigmoid pattern described by Marani and Ephrath (1985). Initial vegetative regrowth produced an exponential increase in plant height. As reproductive development began, vegetative development slowed and the increase in plant height changed from exponential and approached a static level thus forming a sigmoid growth pattern.

Figure 4.3.4 **Development of Plant Height in Siokra 1-4 Cotton Following Simulated Hail Damage (Site: Narrabri, 1991/92)**
(Arrows indicate growth stage for simulated damage)



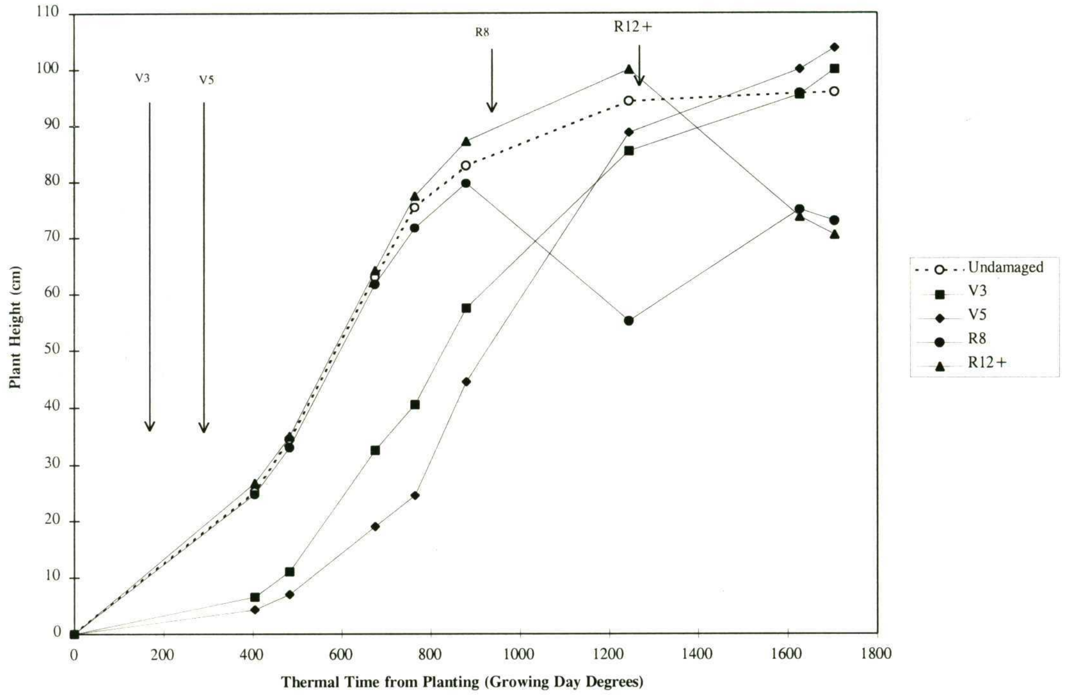
At 521 GDD, l.s.d.$_{(0.001)}$ = 5.33 cm
At 652 GDD, l.s.d.$_{(0.001)}$ = 3.14 cm
At 713 GDD, l.s.d.$_{(0.001)}$ = 3.49 cm
At 983 GDD, l.s.d.$_{(0.001)}$ = 6.50 cm
At 1069 GDD, l.s.d.$_{(0.001)}$ = 4.77 cm
At 1174 GDD, l.s.d.$_{(0.001)}$ = 8.70 cm
At 1308 GDD, l.s.d.$_{(0.001)}$ = 8.15 cm
At 1416 GDD, l.s.d.$_{(0.001)}$ = 10.17 cm
At 1594 GDD, l.s.d.$_{(0.001)}$ = 6.48 cm
At 1798 GDD, l.s.d.$_{(0.001)}$ = 12.47 cm

Figure 4.3.5 **Development of Plant Height in Deltapine 90 Cotton Following Simulated Hail Damage (Site: Narrabri, 1992/93)**
(Arrows indicate growth stage for simulated damage)



At 483 GDD, l.s.d.$_{(0.001)}$ = 3.71 cm
At 674 GDD, l.s.d. $_{(0.001)}$ = 6.40 cm
At 1245 GDD, l.s.d. $_{(0.001)}$ = 12.65 cm
At 1705 GDD, l.s.d. $_{(0.001)}$ = 10.80 cm

Figure 4.3.6 **Development of Plant Height in Siokra 1-4 Cotton Following Simulated Hail Damage (Site: Narrabri, 1992/93)**
(Arrows indicate growth stage for simulated damage)



At 483 GDD, l.s.d.$_{(0.001)}$ = 3.71 cm
At 674 GDD, l.s.d. $_{(0.001)}$ = 6.40 cm
At 1245 GDD, l.s.d. $_{(0.001)}$ = 12.65 cm
At 1705 GDD, l.s.d. $_{(0.001)}$ = 10.80 cm

After the delay in development, the crop regrew under the warm temperatures experienced, growth was rapid and final plant height was increased compared to undamaged cotton (Figures 4.3.3 - 4.3.6). In both seasons, weather conditions allowed plants damaged at the V3 and V5 stages to recover and complete their developmental cycles, producing larger and more vegetative plants with greater final plant height than undamaged plants ($P < 0.001$).

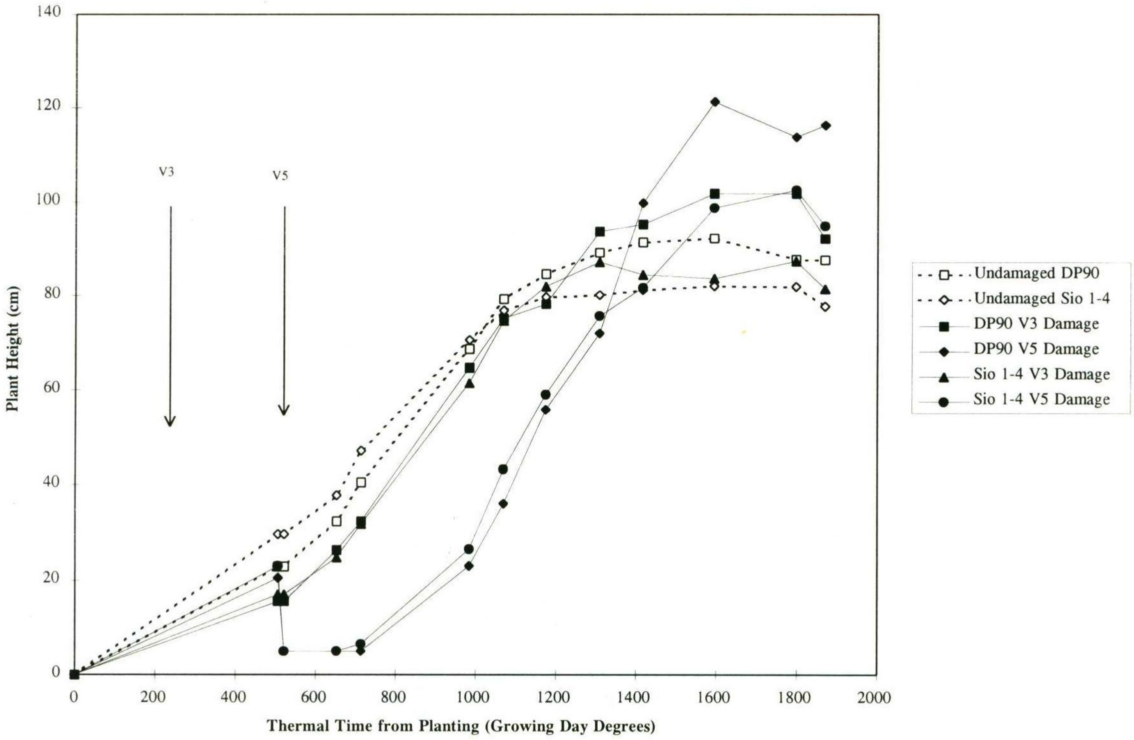
Increased dry matter production is recorded where cotton is planted at delayed sowing dates under warmer temperature conditions (Stern, 1965). My experiments suggest that the increased vegetative growth is also a crop compensation response following vegetative stage simulated hail damage. It is similar to that found following simulated vegetative stage insect damage. Fruit removal or debudding of cotton plants in the simulation of insect damage in cotton consistently increased vegetative growth and concurrently increased floral bud initiation (Eaton, 1931; Dunnan, 1943; Dale, 1959; Ehlig, 1969; Evenson, 1969; Wilson *et al.*, 1972; Malik *et al.*, 1981; Kletter and Wallach; 1982). The increased vegetative growth is characterised by an increase in the number of monopodial branches produced per plant (Dale, 1959; Evenson, 1969), increased plant height via increased internode length (Ehlig, 1969) and increased number of main stem nodes (Malik *et al.*, 1981). Hence, the overall effect is to produce a larger plant of a greater dry weight than undamaged plants. Similar changes in plant morphology were observed following simulated hail damage in these experiments.

The degree of compensatory growth is dependent on the timing of damage as indicated by the difference in increased plant height following damage in the vegetative stages compared to that in the reproductive stages ($P < 0.001$). Hail damage simulations at the R8 and R12+ growth stages produced an entirely different response in terms of plant height compared to vegetative stage damage. With the crop already in the boll setting phase, reproductive development dominated over further vegetative development. Following damage at the R8 stage, replacement of lost vegetative material (ie. increase in plant height) was minimal and, after damage at the R12+ stage, no increase in plant height was measured (Figures 4.3.3 - 4.3.6). The boll load is suggested as having dampened the vegetative regrowth of cotton following partial fruit removal as reported by Ehlig and LeMert (1973); Unger *et al.*, (1987); Patterson *et al.* (1978) and Wilson and Bishop (1982). Hence, increases in plant height following reproductive stage simulated haildamage would be expected to be minimal.

The cotton cultivars used in this work differ in growth characteristics and maturity (Gilbert, 1986; Thomson, 1986). Differences in vegetative development were measured between Deltapine 90 and Siokra 1-4 following simulated hail damage (Figures 4.3.7 - 4.3.10). However, the same patterns of plant height growth are found in undamaged and normally growing cotton. Following simulated hail damage, Siokra 1-4 initially grew taller compared to Deltapine 90, until the vegetative development of Siokra 1-4 slowed as it entered its boll setting phase. Deltapine 90 continued to grow vegetatively after Siokra 1-4 had reached its peak plant height and hence produced a taller final plant height.

Figure 4.3.7 Development of Plant Height in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage in the Vegetative Growth Stages (Site: Narrabri, 1991/92)

(Arrows indicate growth stage for simulated damage)

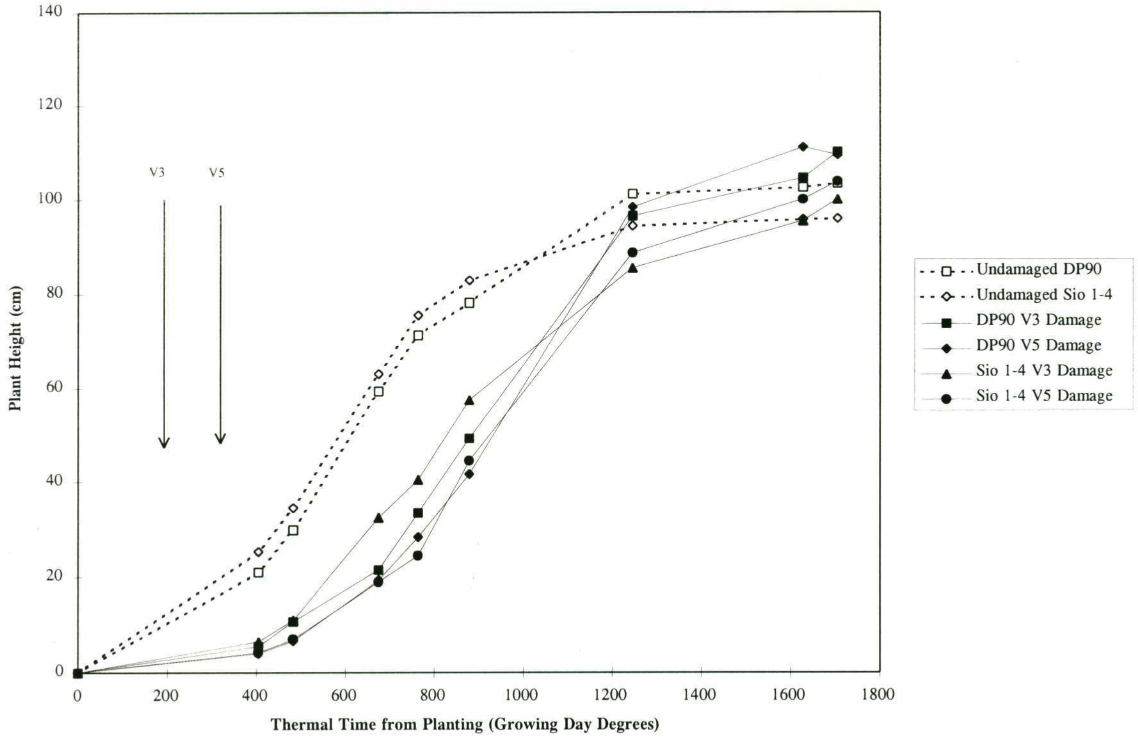


At 521 GDD, l.s.d.$_{(0.001)}$ = 5.33 cm
At 652 GDD, l.s.d.$_{(0.001)}$ = 3.14 cm
At 713 GDD, l.s.d.$_{(0.001)}$ = 3.49 cm
At 983 GDD, l.s.d.$_{(0.001)}$ = 6.50 cm
At 1069 GDD, l.s.d.$_{(0.001)}$ = 4.77 cm

At 1174 GDD, l.s.d.$_{(0.001)}$ = 8.70 cm
At 1308 GDD, l.s.d.$_{(0.001)}$ = 8.15 cm
At 1416 GDD, l.s.d.$_{(0.001)}$ = 10.17 cm
At 1594 GDD, l.s.d.$_{(0.001)}$ = 6.48 cm
At 1798 GDD, l.s.d.$_{(0.001)}$ = 12.47 cm

Figure 4.3.8 **Development of Plant Height in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage in the Vegetative Growth Stages (Site: Narrabri, 1992/93)**

(Arrows indicate growth stage for simulated damage)



At 483 GDD, l.s.d.$_{(0.001)}$ = 3.71 cm

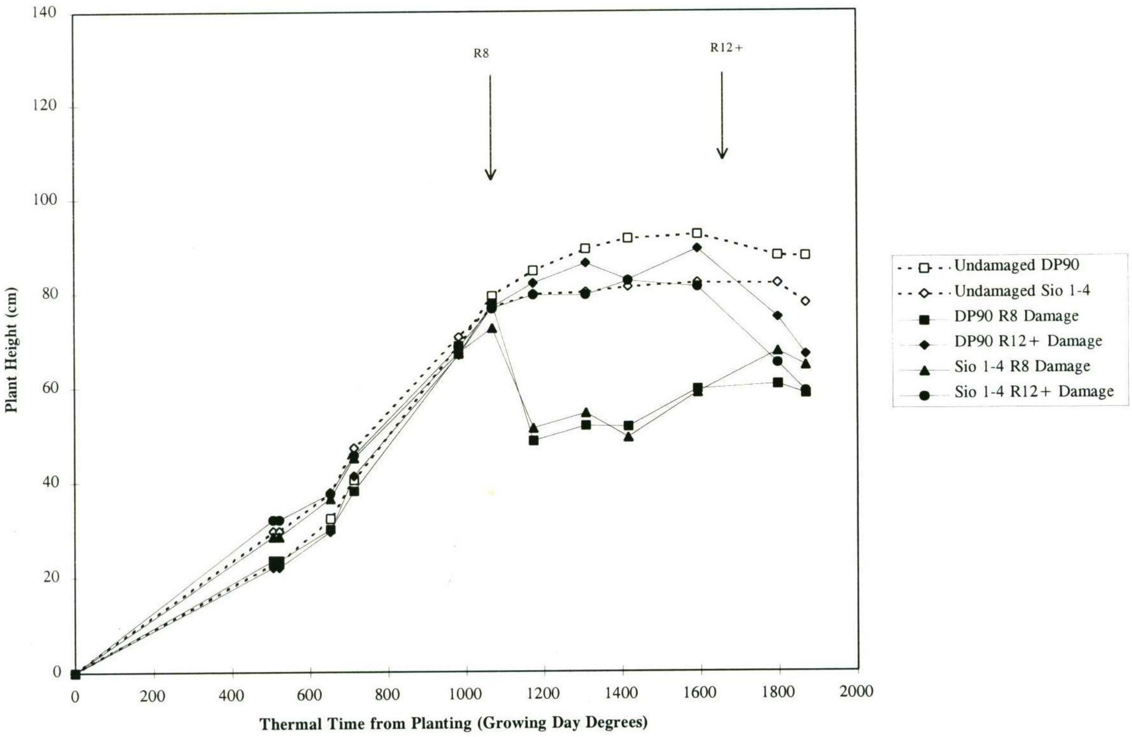
At 674 GDD, l.s.d. $_{(0.001)}$ = 6.40 cm

At 1245 GDD, l.s.d. $_{(0.001)}$ = 12.65 cm

At 1705 GDD, l.s.d. $_{(0.001)}$ = 10.80 cm

Figure 4.3.9 **Development of Plant Height in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage in the Reproductive Growth Stages (Site: Narrabri, 1991/92)**

(Arrows indicate growth stage for simulated damage)

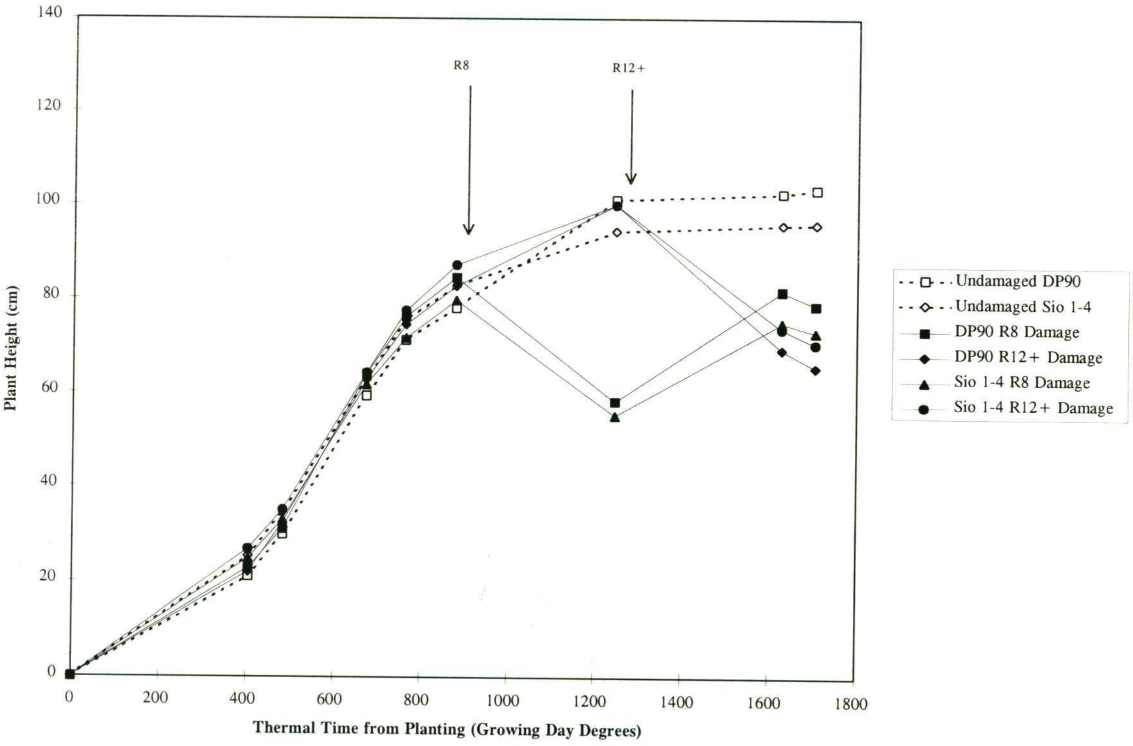


At 521 GDD, l.s.d.$_{(0.001)}$ = 5.33 cm
At 652 GDD, l.s.d.$_{(0.001)}$ = 3.14 cm
At 713 GDD, l.s.d.$_{(0.001)}$ = 3.49 cm
At 983 GDD, l.s.d.$_{(0.001)}$ = 6.50 cm
At 1069 GDD, l.s.d.$_{(0.001)}$ = 4.77 cm

At 1174 GDD, l.s.d.$_{(0.001)}$ = 8.70 cm
At 1308 GDD, l.s.d.$_{(0.001)}$ = 8.15 cm
At 1416 GDD, l.s.d.$_{(0.001)}$ = 10.17 cm
At 1594 GDD, l.s.d.$_{(0.001)}$ = 6.48 cm
At 1798 GDD, l.s.d.$_{(0.001)}$ = 12.47 cm

The same more rapid initial growth in plant height by Siokra 1-4 is recorded following damage at all four growth stages, although the difference is greater after vegetative stage damage simulations. No changes in growth pattern or development between cultivars occurred following simulated hail damage were measured in this work. No significant increase or decrease in delay to initiation of regrowth is measured between the cultivars following the damage simulations. Both cultivars behaved similarly with respect to plant height following simulated hail damage.

Figure 4.3.10 Development of Plant Height in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage in the Reproductive Growth Stages (Site: Narrabri 1992/93)
(Arrows indicate growth stage for simulated damage)



At 483 GDD, l.s.d.$_{(0.001)}$ = 3.71 cm
At 674 GDD, l.s.d. $_{(0.001)}$ = 6.40 cm

At 1245 GDD, l.s.d. $_{(0.001)}$ = 12.65 cm
At 1705 GDD, l.s.d. $_{(0.001)}$ = 10.80 cm

Previous studies have not looked at the full development cycle of cotton varieties following damage. Kittock *et al.* (1976) noted large differences in vegetative growth between Pima cotton varieties *(Gossypium barbadense L.)* measured five weeks after hail damage, but no comparison was made with undamaged cotton of the same varieties nor of final plant height to determine if any change in growth pattern had occurred following hail damage. My work suggests that the differences in vegetative growth reported by Kittock *et al.* (1976) may have been characteristic of the normal growth pattern of the varieties and not a response to hail damage.

Cotton has an indeterminate growth habit and vegetative development consists not only of increases in plant height but also lateral vegetative growth and development of leaf area. Changes in leaf area development in cotton varieties following simulated hail damage was also studied in this work (Chapter 5). From the monitoring of plant height development following simulated hail damage, I conclude that there is an initial delay in regrowth after damage as damaged tissue is repaired and new growing points [meristems] are initiated. Although delayed, plant height development then continued in the sigmoid pattern described by Marani and Ephrath (1985).

In summary, the response to damage is different with damage at the four growth stages examined. With damage in the vegetative growth stages and regrowth under warmer temperature conditions regrowth is rapid and vegetative growth is increased above that of undamaged cotton producing a plant of greater final plant height. With damage in the reproductive stages, vegetative regrowth is reduced and increases in plant height following simulated damage are minimal. A comparison of the regrowth of the two cotton cultivars, Siokra 1-4 and Deltapine 90, shows regrowth in terms of plant height follows the same pattern as undamaged cotton.

Chapter 5

Leaf Area Development in Cotton Varieties after Damage by Simulated Hail

5.1: Introduction

The maximum quantity and rate of carbohydrate production in a crop is determined in part by the amount of sunlight intercepted by the crop. Sunlight is intercepted by the leaves making up the crop canopy. In development of the cotton plant, each node on the main stem and branches subtends a leaf. Leaves in the average cotton crop appear at a relatively constant rate of one per 2.91 days (or 41 GDD) and reach their mature size 2-3 weeks after unfolding (Constable, 1986; Mutsaers, 1983). The largest size leaves are found in the middle of the canopy but overall leaf size is increased in crops of low plant density or late planting (Constable and Rawson, 1980).

Growth in leaf area of a crop typically follows a sigmoid pattern as described by Ashley *et al.* (1965), Constable and Gleeson (1977), Mutsaers (1983) and Stern (1965). Peak Leaf Area Index (LAI) occurs 3 to 5 weeks after the start of flowering and varies from 0.5 in a water stressed crop to more than 6 for a well fertilised and irrigated crop (Constable and Hearn, 1984). Rates of leaf expansion, rate of increase in LAI and rate of decline of LAI as the crop matures were found to vary considerably between seasons and between varieties and planting densities (Constable and Gleeson, 1977; Hearn, 1972).

Reproductive growth contributing to lint yield in cotton is dependent on concurrent growth of vegetative material (Ashley *et al.*, 1965; Oosterhuis and Wullschleger, 1988). Reports of the optimum LAI for maximum yield vary and relate to growing conditions and variety. Crowther (1934) cited by Ashley *et al.* (1965) found an LAI value of 2.0 was optimum for production in *G. barbadense*. More recent work with *G. hirsutum* cottons includes that of Hearn (1972) who reported maximum crop growth rates in cotton correlated with an LAI value of 2.8. Similarly, Constable and Gleeson (1977) found maximum crop growth rates at an LAI of 3.0, occurred approximately 20 days before peak LAI and corresponded to the time of the start of boll growth. Ludwig *et al.* (1965) found temperature affected the optimum LAI for high photosynthetic rates, net photosynthesis increased up to LAI of 3-4 under a range of temperature conditions. Under optimum temperature conditions (25-30 ^{0}C) high levels of photosynthesis were maintained up to an LAI of 7.6, but as temperatures increased above 30 ^{0}C, net photosynthesis only increased up to LAI values of 5.4.

Net photosynthesis is directly related to the amount of light intercepted by the leaf area of the crop (Baker and Meyer, 1966). Monsi and Saeki (1953) cited by Saeki (1960) determined that the light intercepted by the canopy can be expressed as a function of the leaf area index according to Beer's Law:

$$I/I_0 = \mathrm{Exp}(-k.\mathrm{LAI})$$

Where I_0 is the quantity of light incident above the canopy and I is the quantity of light incident at soil level. 'k' is the extinction coefficient for the crop and is determined by the transmissibility, arrangement and inclination of leaves. Hence, the leaf area index of a crop can be measured indirectly by light interception methods. Changes in leaf area can be predicted by observing the changes in the amount of light transmitted through the crop canopy.

Saeki (1960) determined that the extinction coefficient, '*k*' is smaller in crops with upright leaves and larger in plants with more prostrate habit, and concluded that '*k*' is constant for a given species of plant. Saeki (1963) as cited by Hearn (1972) determined '*k*' for cotton to be 0.6, while Ludwig *et al.*, (1965) calculated a value of 1.06. Hearn (1969) in calculating cotton crop growth rates used both these values of '*k*' and concluded from his results that a '*k*' value of 0.6 may be more suitable in crops with LAI values up to 2.0 and a '*k*' value of 1.06 rates for crops with LAI over 2.0. He suggested that the value of the extinction coefficient may change with the age and size of the crop. In later work, Hearn did not confirm this hypothesis but found '*k*' to be constant at 1.12 (Hearn, 1972).

Cotton leaves are heliotropic and hence follow the movement of the sun to maximise photosynthesis (Fukai and Loomis, 1976). Beer's Law holds as long as flux density and angle of incidence of incoming radiation is relatively constant (Baker and Meyer, 1966). Constable (1986) confirmed that although displaying heliotropism, the amount of light intercepted by a leaf varies through the day but is relatively constant in the period around solar noon and it is during this period that measurements employing Beer's Law are most accurate.

Beer's law also assumes a random distribution of light absorbing material and hence does not hold in young row crops. Constable (1986) also found '*k*' to vary with plant density and suggested that '*k*' may increase with increased LAI. Milroy and Sadras (pers comm) suggest that the variation in the extinction coefficient 'k' reported by Constable (1986) and Hearn (1969) is related to boll load and that '*k*' increases as the boll load of the crop increases. When boll load is increased on a given fruiting branch of the cotton plant, the angle at which the branch is held relative to the main stem increase, and likewise the leaves subtended on that branch become held closer to the horizontal plane and hence '*k*' is increased. This hypothesis is consistent with the work of Marani and Ephrath (1985) who observed a rapid change in plant canopy width corresponding to the onset of the boll fill period and a corresponding change in the pattern of light interception by the cotton canopy.

Cotton varieties differ in growth and fruiting patterns and by incorporating the okra leaf characteristic into Siokra 1-4 and its related lines, breeders have conferred decreased plant height and vegetative branch number, increased rate of fruiting and earlier crop maturity compared to the Acala type lines such as Deltapine 90 (Thomson, 1995). Varietal differences in the rate of replacement of leaf material lost by hail damage have been observed in commercial cotton crops in Australia (Cotton Research and Development Corporation, 1990, unpublished). The aim of this study was to identify differences in the development of the leaf canopy in cotton varieties after damage to the canopy by simulated hail damage. Leaf area of damaged cotton was estimated by light interception measurements.

5.2: Methods

Experiments were carried out at the Australian Cotton Research Institute, Narrabri, Australia (149^0 47' E, 30^0 13' S) during the 1991/92 and 1992/93 cotton seasons to examine the regrowth of cotton varieties after simulated hail damage as described in Chapter 3. Destructive leaf area samples were taken from one metre square areas of crop in undamaged plots at 7-10 day intervals from approximately 30 days after planting through to the day of the last irrigation. Light interception by the leaf canopy was measured in these control plots using a Li-Cor leaf area meter.

Leaf area development for damage simulation treatment plots was monitored indirectly by the light interception method. This method assumes that the quantity of light intercepted by the crop canopy is related to the leaf area of the crop by Beer's Law. Photosynthetically active radiation (PAR) (400 - 700 nm) was measured using a Decagon Sunfleck Ceptometer (Model SF-40). I/I_0 was calculated by measuring average PAR incident at the crop canopy surface (I_0) and that reaching the soil surface below the crop (I). Measurements being made over one metre square areas.

PAR sample dates corresponded to the period of fruit load development and the extinction coefficient '*k*' was found to vary across sample dates, increasing with boll load and time after planting as presented in Figures 5.2.1 and 5.2.2.

In the undamaged (control) treatments for each season, both LAI and I/I_0 were measured directly and thus enabled the calculation of '*k*' for each sample date. Total boll load or boll number for each date was also known. By regressing boll number on known '*k*' values, regression equations were used to estimate '*k*' for each variety for each sample date for the treated plots (Table 5.2.1).

Figure 5.2.1 Variation in Measured Extinction Coefficient '*k*' (Site: Narrabri, 1991/92)

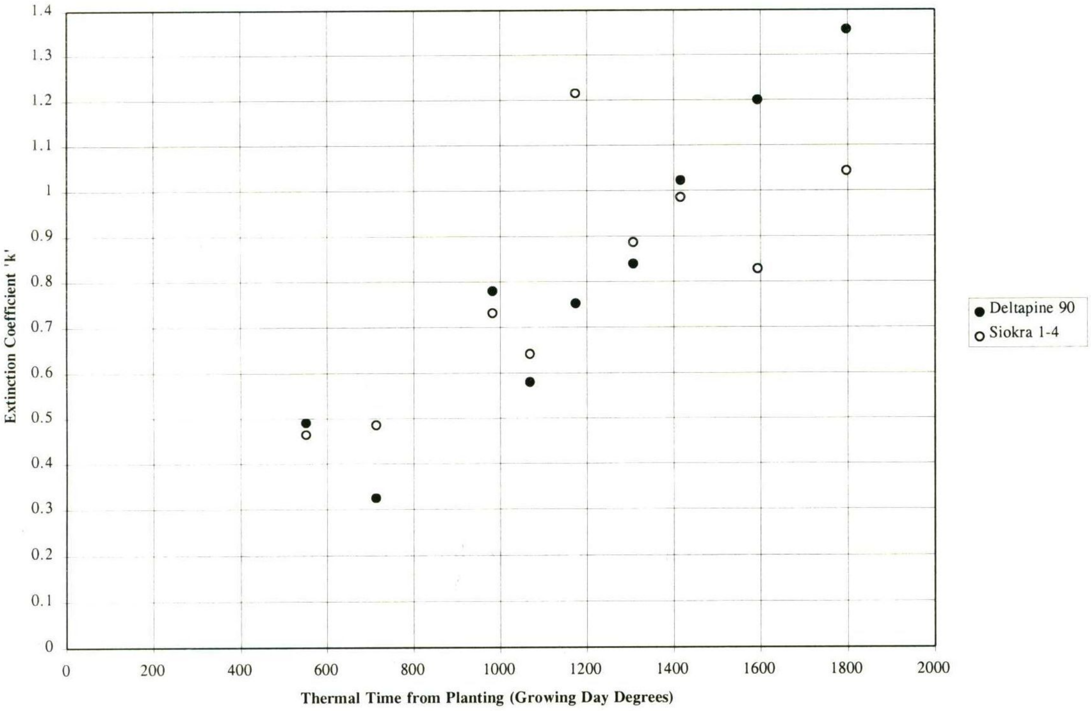


Figure 5.2.2 Variation in Measured Extinction Coefficient '*k*' (Site: Narrabri, 1992/93)

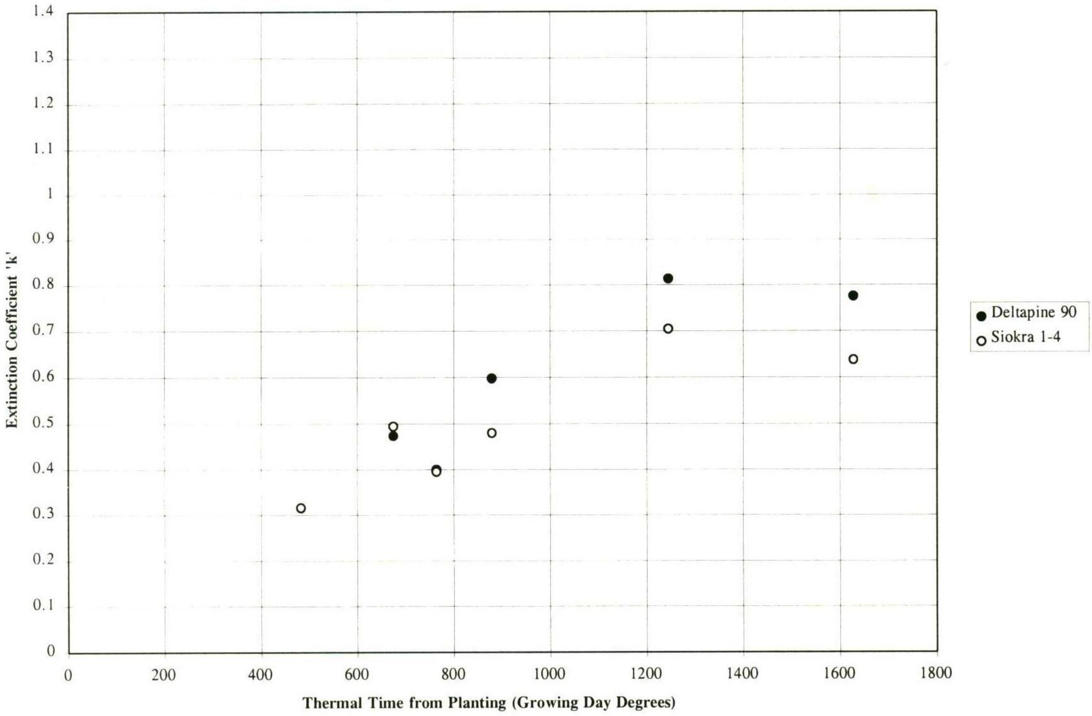


Table 5.2.1 **Regression Equations for the Extinction Coefficient '*k*' as related to Boll Load.***

	1991/92	r^2	**1992/93**	r^2
Deltapine 90	$k = 0.409 + 0.00600$ x Boll Number	91.8%	$k = 0.485 + 0.00276$ x Boll Number	97.4%
Siokra 1-4	$k = 0.473 + 0.00430$ x Boll Number	99.8%	$k = 0.351 + 0.00257$ x Boll Number	95.9%

* The quadratic regression model did not improve the fit over a linear model.

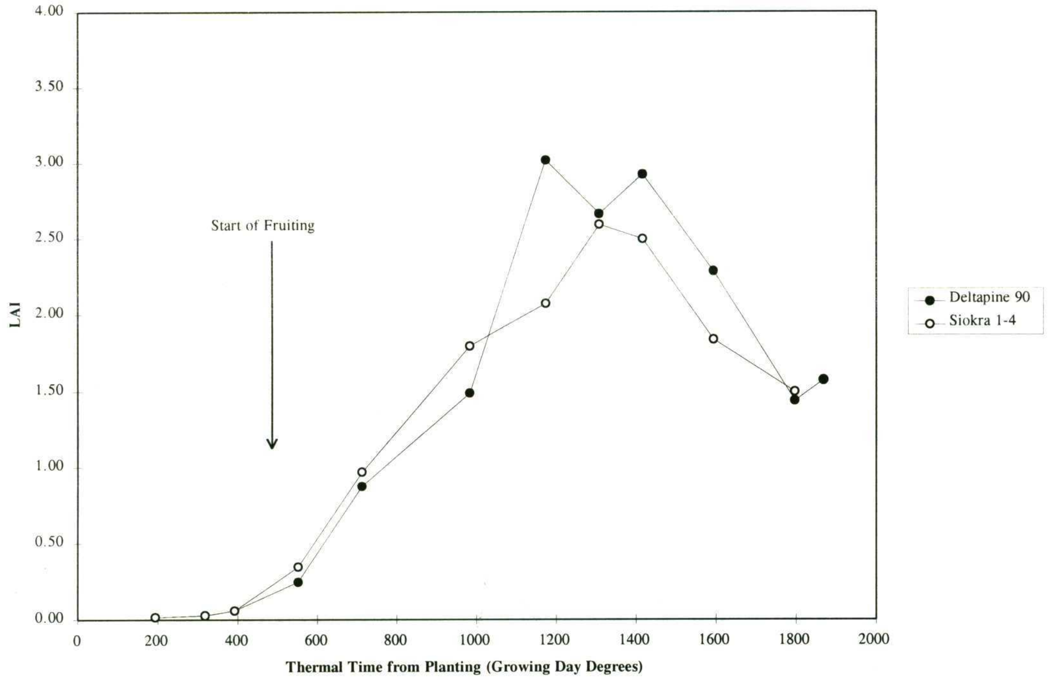
5.3: Results and Discussion

Leaf area development patterns for Deltapine 90 and Siokra 1-4 measured in the two experiments are presented in Figures 5.3.1 and 5.3.2. They followed the typical sigmoid patterns of leaf canopy development described by Ashley *et al.*, (1965); Constable and Gleeson, (1977), Mutsaers (1983) and Stern (1964).

In 1991/92, LAI of DP90 reached a peak of 3.02 at 1170 Growing Day Degrees (GDD) from planting before declining to 1.57 at defoliation. Siokra 1-4 initially grew more rapidly in terms of leaf area and reached a peak LAI of 2.59 at approximately 1300 GDD after planting and declining to 1.50 at defoliation (Figure 5.3.1). Light intercepted by the canopy of Siokra 1-4 was only significantly greater than Deltapine 90 at samples dates 551 and 714 GDD after planting ($P < 0.01$). A three week period of cloudy weather resulted in leaf loss between 1200 and 1400 GDD after planting. Cotton is inherently intolerant of shading and acts to shed leaf and young fruit in overcast and wet weather conditions (Stern, 1965). The overcast conditions experienced from 1200 to 1400 GDD from planting reduced the number of days available for light interception data to be collected and effectively reduced the data available for the estimation of LAI and hence the detail of leaf area growth patterns.

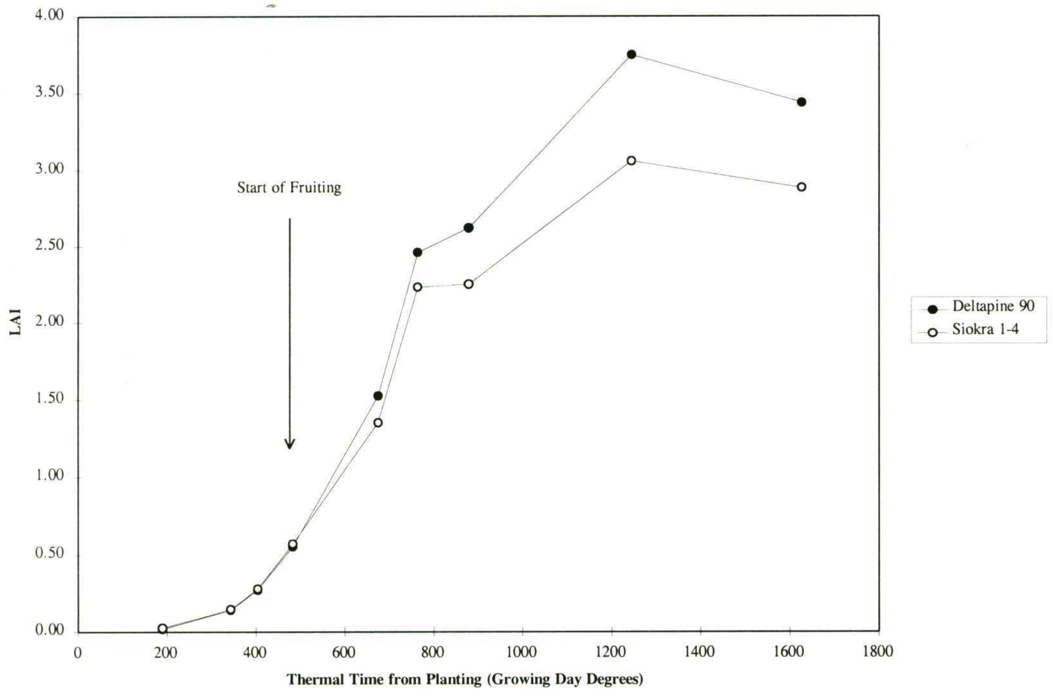
In 1992/93, LAI values for cultivars were similar in the initial stages of growth (Figure 5.3.2). At 879 and 1254 GDD after planting, light intercepted by Deltapine 90 was significantly greater than that intercepted by Siokra 1-4 ($P < 0.01$ and $P < 0.05$ for the two dates, respectively) indicating a significantly greater leaf area for Deltapine 90 at these sample dates. LAI of Deltapine 90 peaked at approximately 1250 GDD after planting at an LAI of 3.66 before declining. LAI of Siokra 1-4 reached a lower peak of 3.06 at the same sample date.

Figure 5.3.1 **Comparative Development of LAI in Deltapine 90 and Siokra 1-4 Cotton Cultivars (Site: Narrabri, 1991/92)**



Differences in leaf area between cultivars at each sampling point were not significantly different.

Figure 5.3.2 **Comparative Development of LAI in Deltapine 90 and Siokra 1-4 Cotton Cultivars (Site: Narrabri, 1992/93)**



At 879 GDD, l.s.d.(0.1) = 0.376
At 1254 GDD, l.s.d. (0.05) = 0.243
Differences in leaf area between cultivars at other sampling points were not significantly different.

LAI values were calculated from measured I/I_0 for undamaged cotton using Beer's Law (Tables 5.3.1, 5.3.2). The extinction coefficient '*k*' was allowed to vary with boll load according the regression equations in Table 5.2.1. A comparison of the calculated LAI values with actual measured LAI for the undamaged cotton is presented in Figures 5.3.3 and 5.3.4. The LAI values estimated using Beer's Law are in close agreement with actual values in 1992/93. Calculated values deviate from the actual LAI values around the sample date of 1069 GDD from planting in the 1991/92 season where sampling problems were experienced.

LAI values for hail damage simulated at the various growth stages, estimated from I/I_0 using Beer's Law, are presented in Tables 5.3.1 and 5.3.2.

According to estimated LAI values, regrowth of leaf material was delayed for a period 100-150 GDD following damage (Figure 5.3.5). Although the whole LAI development curve was moved further into the season by 100-150 GDD (ie. thermal time for development increased), once leaf regrowth was initiated, LAI development followed the same general sigmoid pattern as in undamaged cotton. Siokra 1-4 displayed an initial more rapid rate of leaf material replacement extending for a period of 200 GDD following damage at the V3 and V5 stages (Figure 5.3.5).

After this initial phase of regrowth, the LAI of Deltapine 90 increased faster relative to Siokra 1-4, resulting in a higher peak LAI in Deltapine 90 than Siokra 1-4. This is similar to the comparative rates of LAI development in undamaged cotton.

Table 5.3.1 Estimated Leaf Area Index
Site: Narrabri, 1991/92

Thermal Time from Planting (Growing Day Degrees)	Undamaged Actual LAI	Undamaged Estimated LAI	V3 Damage Estimated LAI	V5 Damage Estimated LAI	R8 Damage Estimated LAI	R12+ Damage Estimated LAI
	DELTAPINE 90					
552	0.245	0.293	0.002	0.038	0.305	0.260
714	0.875	0.694	0.215	0.054	0.750	0.838
983	1.487	2.629	1.961	0.292	2.803	2.647
1069	2.505	2.711	1.527	0.185	3.207	2.252
1174	3.017	2.917	2.522	0.779	1.169	2.822
1308	2.659	2.386	2.335	0.883	0.686	2.354
1416	2.922	2.830	2.482	1.128	1.012	3.207
1594	2.284	2.515	2.102	2.169	0.757	2.757
1798	1.435	1.964	2.584	2.470	0.870	1.236
	SIOKRA 1-4					
552	0.341	0.335	0.048	0.022	0.297	0.227
714	0.968	0.992	0.446	0.040	1.022	0.962
983	1.792	2.328	1.371	0.409	2.252	2.230
1069	2.034	2.021	1.766	0.341	2.155	1.866
1174	1.866	2.754	2.542	0.777	0.886	2.996
1308	2.070	2.049	2.106	1.221	0.292	2.697
1416	2.588	2.610	2.465	1.689	1.004	2.775
1594	2.494	2.200	2.859	2.137	1.034	2.469
1798	1.835	2.179	1.778	2.638	1.159	1.261

Table 5.3.2 Estimated Leaf Area Index
Site: Narrabri, 1992/93

Thermal Time from Planting (Growing Day Degrees)	Undamaged Actual LAI	Undamaged Estimated LAI	V3 Damage Estimated LAI	V5 Damage Estimated LAI	R8 Damage Estimated LAI	R12+ Damage Estimated LAI
	DELTAPINE 90					
483	0.552	0.359	0.000	0.015	0.300	0.387
675	1.523	1.476	0.193	0.081	1.899	1.613
764	2.459	1.942	0.326	0.430	2.094	2.169
879	2.622	2.688	1.710	1.626	2.475	2.099
1245	3.748	3.657	1.977	2.330	0.882	3.668
1628	3.435	3.533	1.978	3.684	1.727	1.897
	SIOKRA 1-4					
483	0.570	0.514	0.104	0.009	0.604	0.484
675	1.350	1.892	0.343	0.056	1.990	1.478
764	2.235	2.364	0.500	0.428	2.184	2.399
879	2.255	2.279	1.686	2.096	1.406	2.816
1245	3.060	2.957	1.404	2.435	1.001	4.349
1628	2.885	3.028	2.491	3.712	2.223	2.460

Figure 5.3.3 **Comparison of Actual and Estimated LAI for Deltapine 90 and Siokra 1-4 Cotton Cultivars. (Site: Narrabri, 1991/92)**

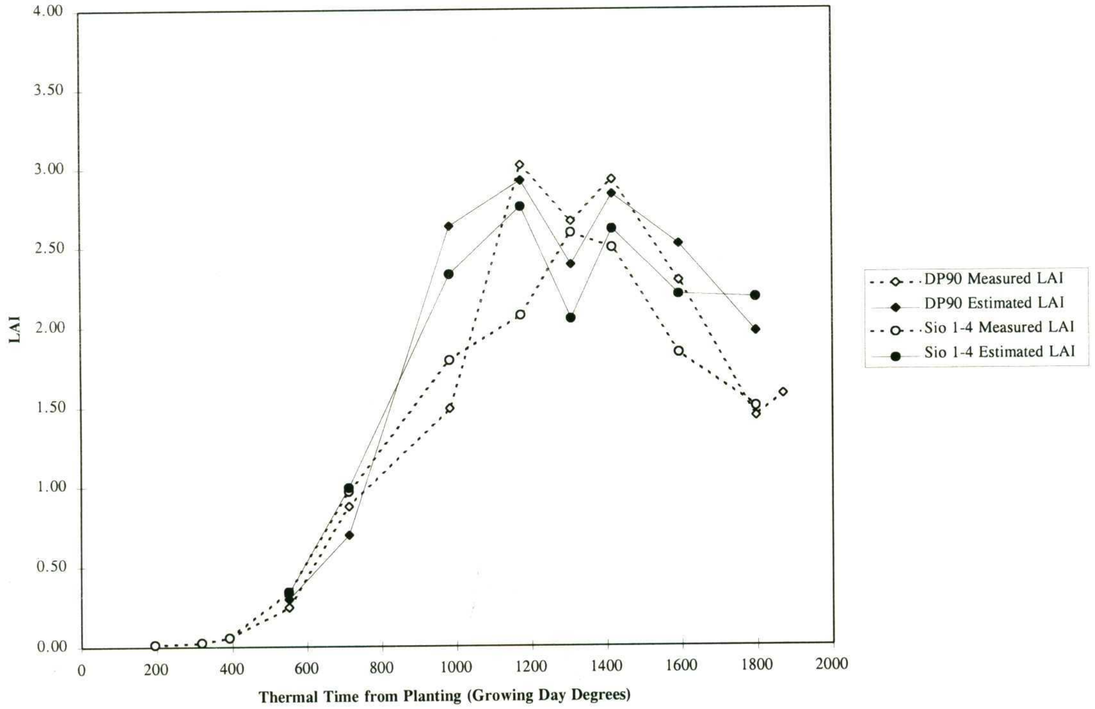


Figure 5.3.4 **Comparison of Actual and Estimated LAI for Deltapine 90 and Siokra 1-4 Cotton Cultivars. (Site: Narrabri, 1992/93)**

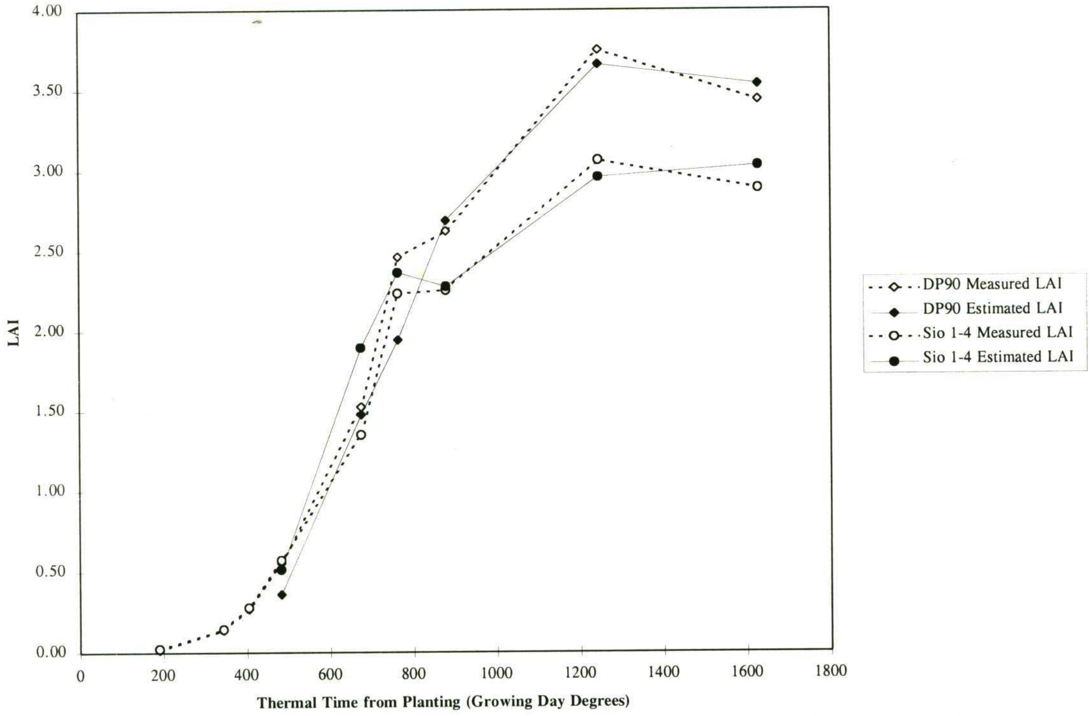


Figure 5.3.5 **Estimated LAI Development after Vegetative Stage Simulated Hail Damage in Deltapine 90 and Siokra 1-4 Cotton Cultivars. (Site: Narrabri, 1991/92)**

(Arrows indicate growth stage and time of simulated damage)

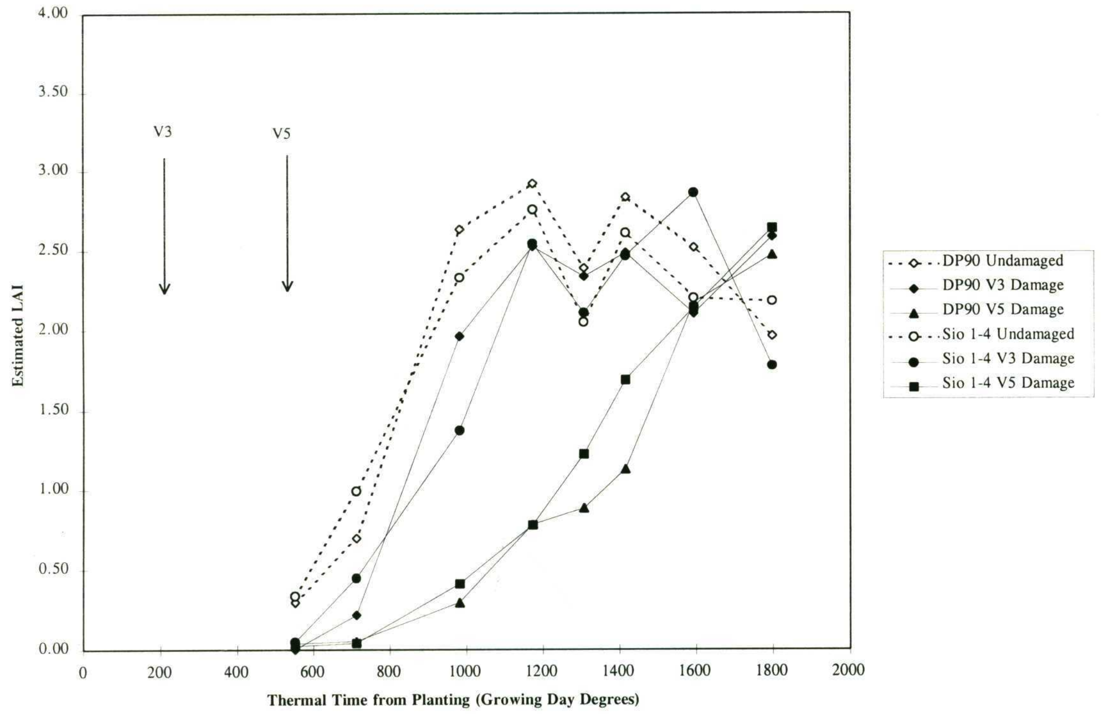
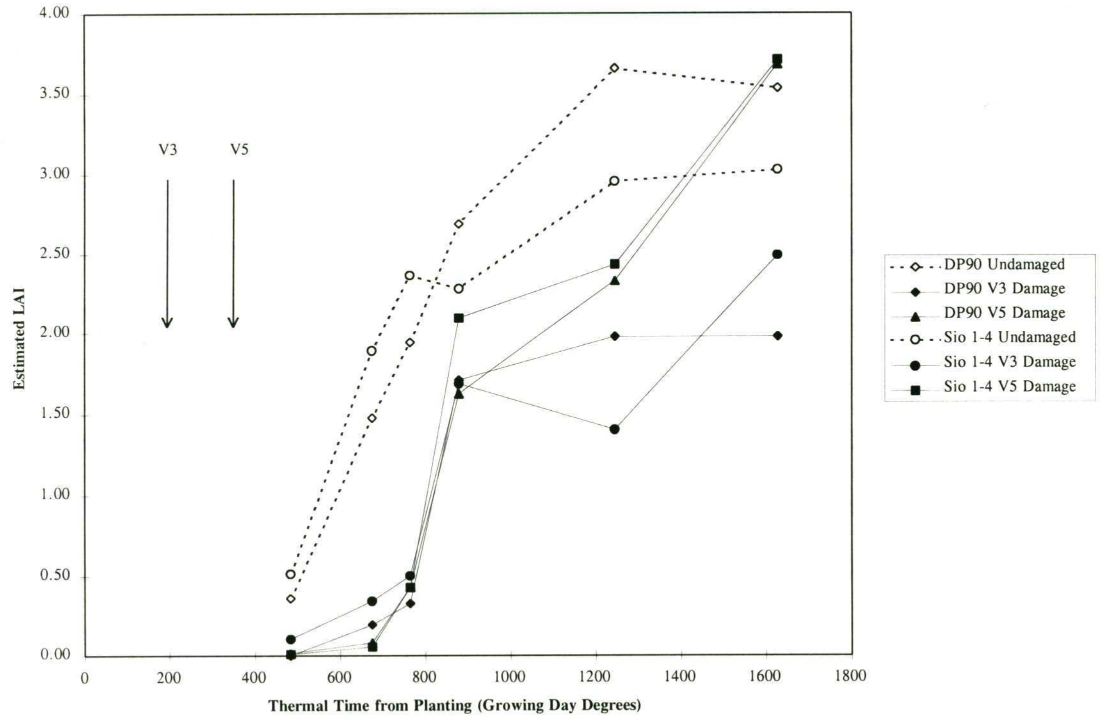


Figure 5.3.6 **Estimated LAI Development after Vegetative Stage Simulated Hail Damage in Deltapine 90 and Siokra 1-4 Cotton Cultivars. (Site: Narrabri, 1992/93)**

(Arrows indicate growth stage and time of simulated damage)



Recovery after damage simulations at the V3 and V5 growth stages was rapid in 1991/92, associated with the warm climatic conditions, non-limiting moisture and high nutrient status. The LAI decrease measured in control plots during the period of adverse weather conditions (between 1200 and 1400 GDD) was mirrored in the estimated values (Figure 5.3.3). The pattern of LAI development deviates from sigmoid at later sampling dates (Figures 5.3.5, 5.3.7). Adverse weather conditions are suggested as the cause of this deviation from the sigmoid pattern.

In 1992/93, following V3 damage, recovery of LAI was similar to that of the previous season (Figure 5.3.6). After the initial delay before the start of replacement of leaf material of approximately 100-150 GDD, LAI increased in Siokra 1-4 at an initially higher rate than Deltapine 90 for a period of 300 GDD. From this point, the LAI of Deltapine 90 increased more quickly than that of Siokra 1-4, ie. similar to the undamaged cotton. Following damage at the V5 stage, LAI increases were similar in both cultivars for a period of 300 GDD, after which LAI of Siokra 1-4 increased more rapidly up to 1200 GDD after planting and then declined compared to Deltapine 90.

Following the initial delay in initiation of new leaf material following damage at the V3 growth stage, leaf material was replaced and LAI reached similar levels to that in undamaged cotton according to estimated LAI values. Following damage at the V5 growth stage, leaf material was replaced and although reached at a much delayed date in the season, maximum LAI approximated the estimated peak LAI for undamaged cotton.

Peak estimated LAI did not exceed that of undamaged cotton except in Siokra 1-4 following V3 stage damage in 1991/92 and V5 stage damage in 1992/93. Estimated LAI had not begun to decline at the last sampling date but was still increasing exponentially. On the other hand, peak LAI had been reached 400-600 GDD earlier in undamaged cotton. This suggests that there was a potential for further vegetative development should climatic conditions allow.

Increased plant height was recorded following vegetative stage simulated hail damage in related measurements in these experiments (Chapter 4) and increased vegetative growth has been recorded following disbudding / defoliation in the simulation of insect damage in cotton (Eaton, 1931; Dunnan, 1943; Dale, 1959; Ehlig, 1969; Evenson, 1969; Wilson, 1972; Malik *et al.*, 1981; Kletter and Wallach; 1982). I interpret increased vegetative growth as a crop compensation response following vegetative stage simulated hail damage. Although estimated peak LAI in vegetative stage damaged cotton did not exceed that of undamaged cotton, the overall effect of high peak LAI and increased plant height was to produce more vegetative plants of larger plant structure in those plants damaged in the vegetative stages. At the time of damage simulation at the R8 or R12 reproductive developmental stages, vegetative growth had slowed overall. There was also reduced available thermal time remaining in the season for the crop to replace material lost by simulated hail damage.

Following simulation of damage at the R8 growth stage, leaf material was replaced to a limited extent with final LAI values of 1.09 and 2.22 for Siokra 1-4 for the 1991/92 and 1992/93 seasons, respectively. This was compared to final LAI values of 0.87 and 1.73 for Deltapine 90 in each season, respectively. Again Siokra 1-4 showed an initially higher rate of replacement of leaf material. With damage simulated at the R12 stage, when the cotton plant is considered mature, neither cultivar replaced leaf material lost in the damage simulation (Figures 5.3.7 and 5.3.8). Differences in LAI were highly significant between any given damage date for the amount of light intercepted by the crop and hence, estimated LAI ($P < 0.01$).

In using a light interception method to estimate LAI, it has been possible to produce growth patterns similar to actual LAI measured for undamaged cotton. Changes in actual LAI induced by adverse weather conditions were mirrored in estimated values. Therefore, I can conclude that light interception methods can be used in place of actual LAI measurement where it is impractical to sample leaf area of entire experiments. Limitations to the use of the method include sample time for light interception is restricted to solar noon and cloudless days and, therefore, sampling dates available for data collection can be restricted in some areas and under adverse weather conditions.

In my experiments, leaf area development following simulated hail damaged followed similar patterns to that in undamaged cotton. The growth stage of the crop at the time of damage strongly influenced the degree of leaf material replaced following damage. Leaf area development was delayed following hail damage simulation in the vegetative stages but reached a similar maximum LAI although at a delayed date. In contrast, defoliation, due to simulated hail damage in the reproductive stages of growth, resulted in minimal replacement of lost leaf tissue. Varietal differences in the rate of replacement of leaf material lost by hail damage have been observed in commercial cotton crops in Australia (Cotton Research and Development Corporation, 1990, unpublished). This experiment showed that there are inherent differences in the rate of production of leaf material in the two cotton cultivars, Deltapine 90 and Siokra 1-4, although following hail damage similar patterns of leaf development are displayed.

Figure 5.3.7 **Estimated LAI Development after Reproductive Stage Simulated Hail Damage in Deltapine 90 and Siokra 1-4 Cotton Cultivars. (Site: Narrabri, 1991/92)**

(Arrows indicate growth stage and time of simulated damage)

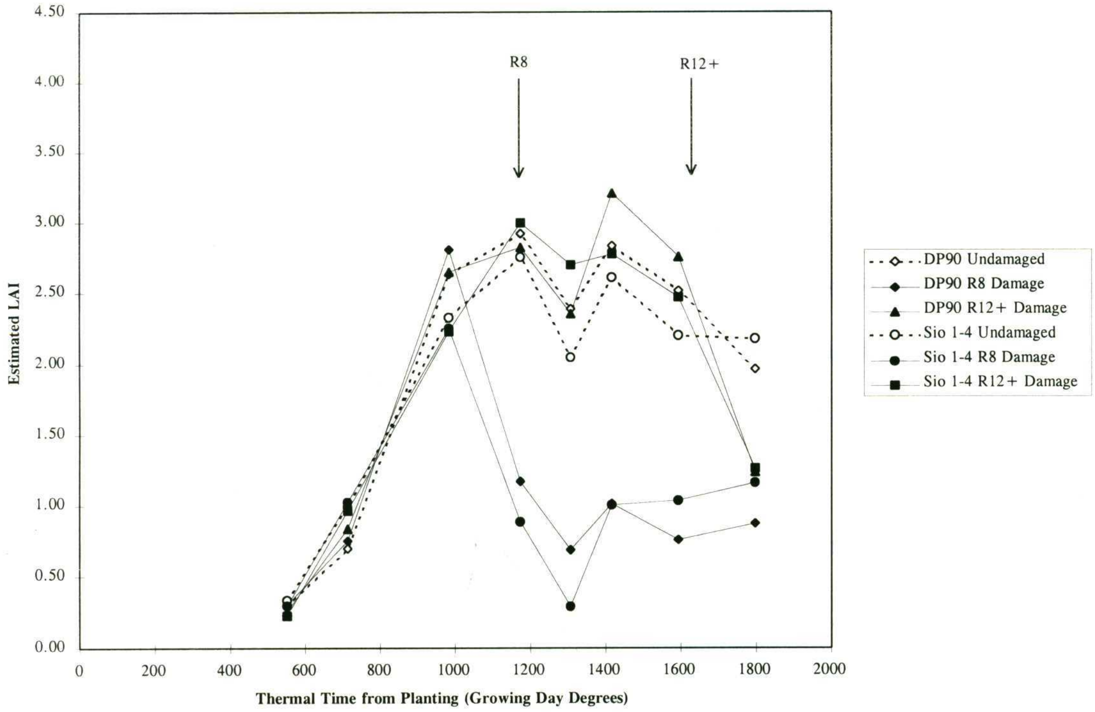
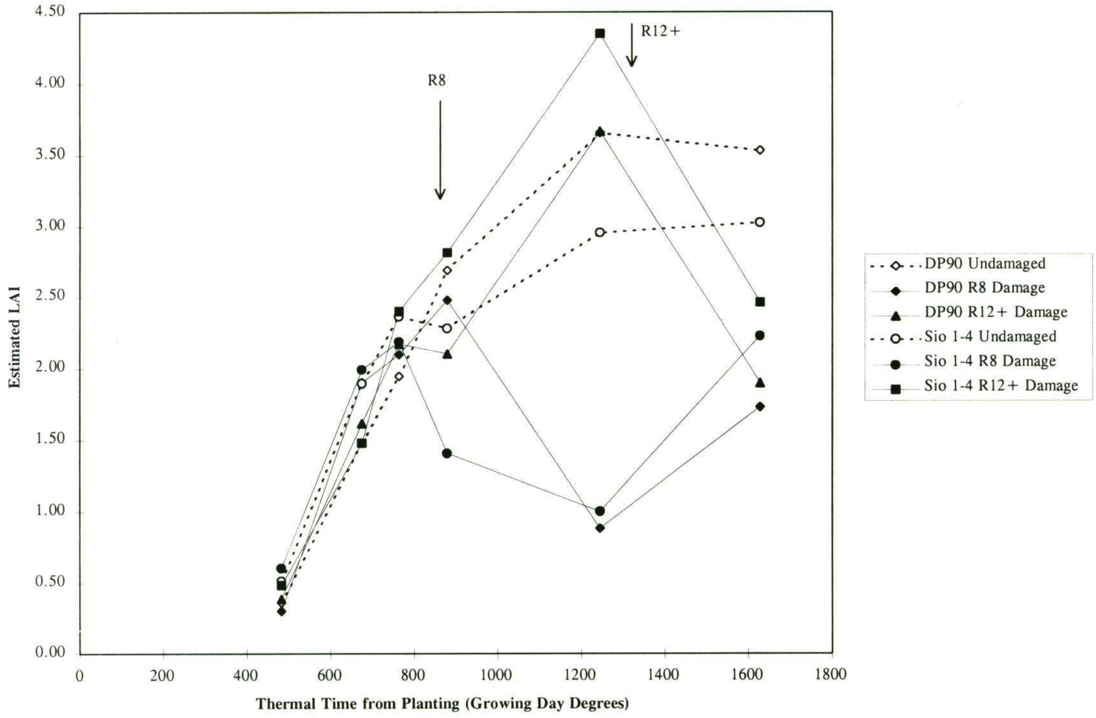


Figure 5.3.8 **Estimated LAI Development after Reproductive Stage Simulated Hail Damage in Deltapine 90 and Siokra 1-4 Cotton Cultivars. (Site: Narrabri, 1992/93)**

(Arrows indicate growth stage and time of simulated damage)



Chapter 6

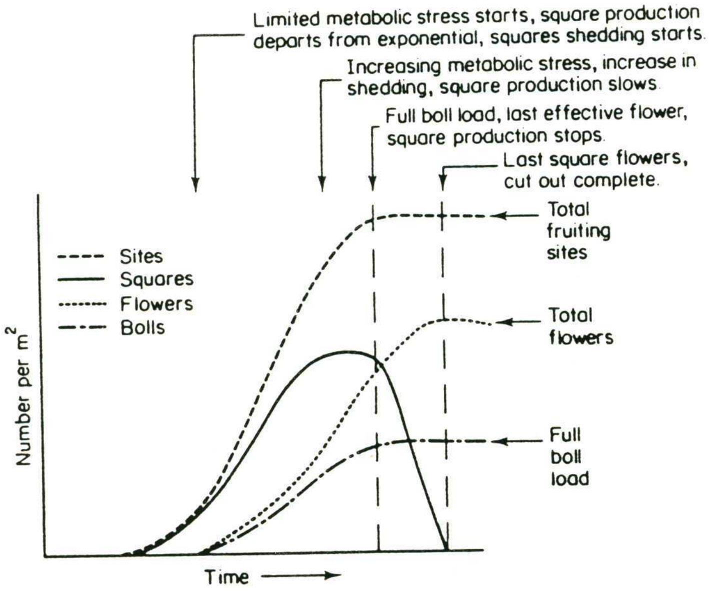
Patterns of Fruit Development in Cotton Varieties after Damage by Simulated Hail

6.1: Introduction

Theoretically, an indeterminate plant has no morphological limit to it's development and no limit to the number of fruiting structures produced. In cotton, flower buds are produced on the sympodial fruiting branches which develop from each of the main stem nodes beginning with the 5th - 8th node, depending on environmental conditions (Hearn, 1979; Mauney, 1986). As the main stem develops, an ever increasing number of flower buds are initiated which have the potential of contributing to lint yield .

In practice, plant development is limited by environmental and physiological factors (Hearn, 1979). Temperature, water and nutrient levels act to limit or restrict physiological processes and hence affect the number and rate of fruit set. The carbohydrate and nitrogen demand of the developing fruit increases exponentially as the plant develops; however, as the supply of carbohydrate and nitrogen is limited, competition for these assimilates develops between the various growing organs of the plant. The rate of flowering and boll set are reduced and fruit that are not set as bolls are shed (Hearn, 1979). Square production stops when the maximum boll load that is attainable with the inputs is reached, and the plant is termed as having reached "cut out" (Hearn, 1979). The pattern of square and fruit production is diagrammatically presented in Figure 6.1.1. The plant may restart and produce a second fruiting phase as bolls mature and no longer act as sinks for assimilates.

Figure 6.1.1: The Pattern of Square and Boll Production
Source: Hearn and Constable (1984).



Although cotton is indeterminate in growth, varieties are classified as determinate or indeterminate depending on their flowering pattern. Determinate varieties fruit heavily during the early season then the growth of fruiting branches and rate of flower production decline. With the first mature bolls begin to open, the determinate plant will usually renew its growth and a second crop will be set. The indeterminate cottons will continue to flower throughout the season but the boll load never becomes sufficiently high to stop growth (Eaton, 1931). Determinate cottons are commonly referred to as 'early' and the indeterminate cottons as 'late'. Due to variation in the length of time to first square, square and boll periods, cotton varieties range in growth pattern from determinate to indeterminate.

Deltapine 90 is classed as a determinate cultivar and develops its fruit load in an even fashion rising to a peak and then falling away without the tendency to enter a secondary fruiting phase (Gilbert, 1985). Siokra 1-4 is also classified as determinate but its okra leaf characteristic confers a 7-10 day earlier maturity than Deltapine 90 through a more rapid flowering rate (Andries *et al.*, 1969; Thomson, 1985; Thomson, 1986). It also produces a greater number of squares and bolls than Deltapine 90, of which a large number are shed (Thomson, 1986).

Varietal differences in the rate of vegetative regrowth after hail damage have been observed in commercial cotton crops in Australia (Cotton Research and Development Corporation, 1990, unpublished). In these experiments (Chapters 4 and 5), Deltapine 90 and Siokra 1-4 cotton cultivars differed in their patterns of vegetative growth and following simulated hail damage, regrowth of vegetative material followed the same pattern as in undamaged cotton. The aim of this study was to examine the fruit development pattern of the two cotton cultivars, Deltapine 90 and Siokra 1-4, and identify differences in fruit development patterns of the cultivars after damage by simulated hail.

6.2: Materials and Methods:

Experiments were carried out at the Australian Cotton Research Institute, Narrabri, Australia (149^0 47' E, 30^0 13' S) during the 1991/92 and 1992/93 cotton seasons examining the regrowth of cotton varieties after simulated hail damage as described in Chapter 3. Hail damage was simulated at four plant growth stages during the season as described previously in Section 3.4. Fruit numbers were monitored in undamaged and simulated hail treatments over one metre square sample areas at 7-10 day intervals to determine fruiting patterns before and after damage.

Fruiting forms were defined as follows:-

Square	- Flower bud from 0.5 cm diameter in size to white flower.
Green boll	- Pink flower to unopened boll of mature size.
Open boll	- mature boll, opened to reveal lint.

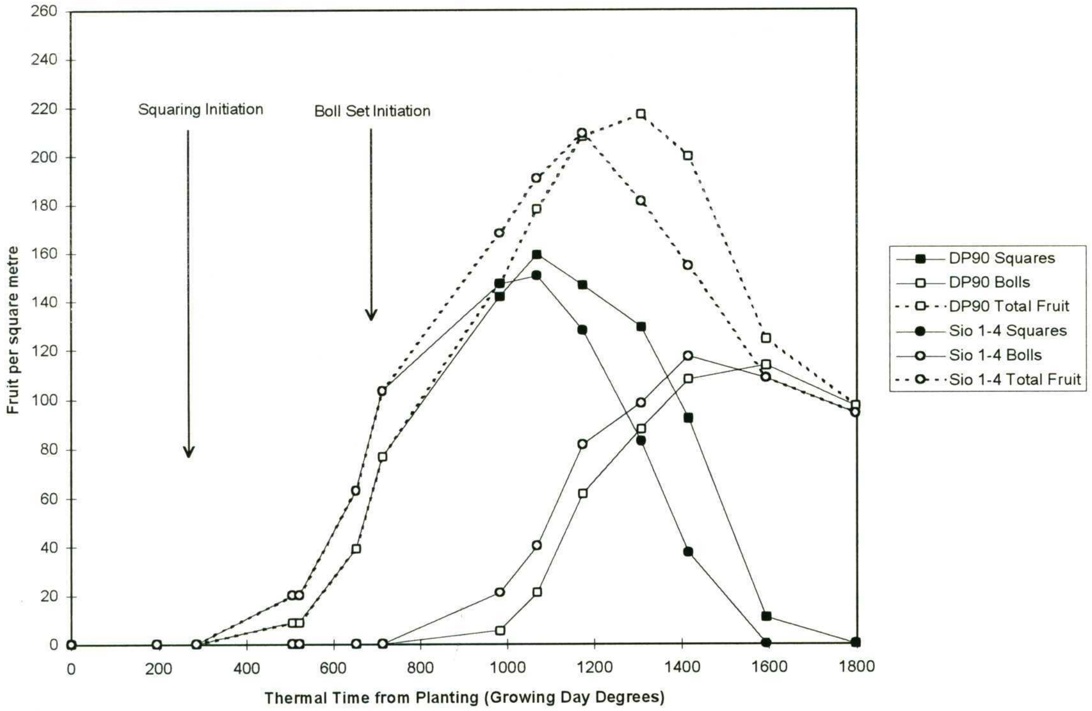
6.3: Results and Discussion

The fruiting patterns of Deltapine 90 and Siokra 1-4 as measured in the experiments carried out at the Australian Cotton Research Institute, Narrabri, Australia during the 1991/92 and 1992/93 season are presented in Figures 6.3.1 and 6.3.2.

Although temperatures were optimal and heat unit accumulation equal to or above average for most of the 1991/92 cotton season, overcast conditions associated with wet weather during December and February depressed squaring and fruit retention rates in these periods (ie. approximately from 700 to 1200 GDD and 1500-1700 GDD from planting, respectively). Cotton has a high radiation requirement and is intolerant of shading (Thomson, 1975). It sheds squares and young fruit and tends to remain vegetative under waterlogged conditions, or conditions of reduced light intensity occurring with shading or cloudy weather overcast and wet weather (Brown and Ware, 1958; Hearn and Constable, 1984; Hearn, 1981; Thomson, 1975). In this experiment, wet and overcast weather acted to modify the fruiting patterns recorded.

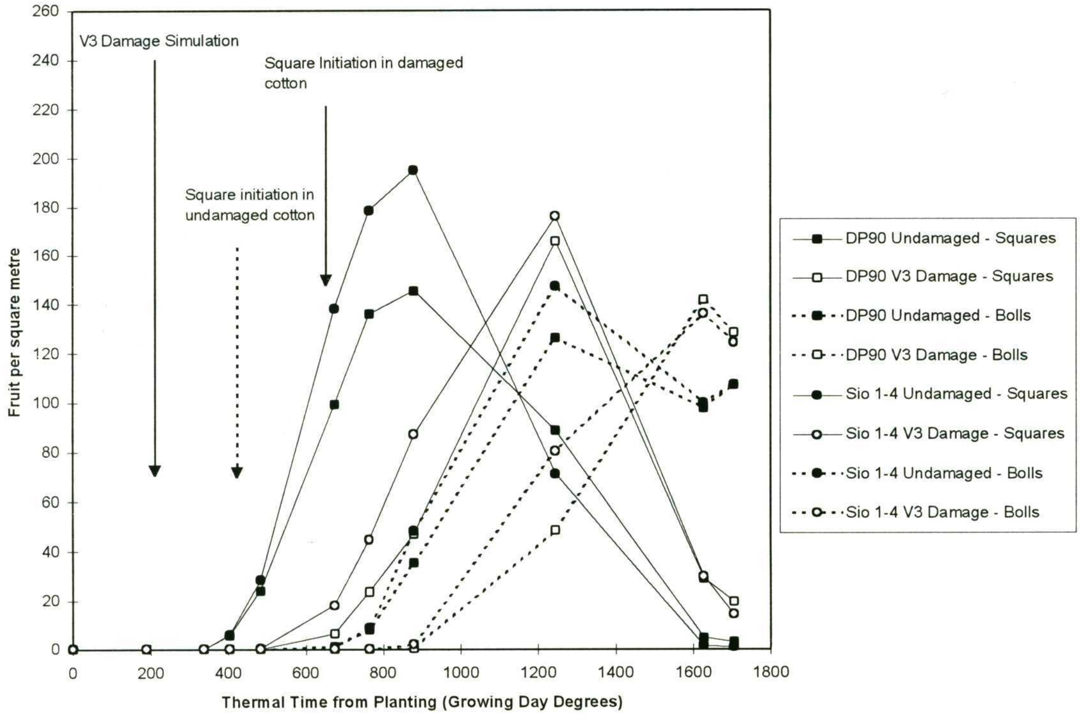
In 1991/92, the two cultivars had similar dates for initiation of squaring; once squaring was initiated Siokra 1-4 squared at a greater rate (Figure 6.3.1). Peak square numbers for Siokra 1-4 were reached at 1070 GDD from planting but at a level lower than is normally seen in field observations for this cultivar. It is suggested that Siokra 1-4 should have reached peak square numbers during the period from approximately 700 - 900 GDD, corresponding to the first period of overcast weather and that the square retention rate of this cultivar was reduced by the weather conditions. Deltapine 90 squared at a slower rate and reached its peak rate and peak square numbers at a later time and as it has an inherently lower fruit shedding characteristic and it was less affected by the overcast conditions.

Figure 6.3.1: Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars (Site: Narrabri, 1991/92)



At 652 GDD, l.s.d.$_{(0.05)}$ = 10.08 squares/m^2 At 983 GDD, l.s.d.$_{(0.05)}$ = 6.87 bolls/m^2
At 713 GDD, l.s.d.$_{(0.05)}$ = 13.0 squares/m^2 At 1069 GDD, l.s.d.$_{(0.05)}$ = 10.18 bolls/m^2
At 1594 GDD, l.s.d.$_{(0.05)}$ = 25.6 squares/m^2 At 1798 GDD, l.s.d.$_{(0.01)}$ = 15.4 bolls/m^2
Differences in fruit numbers between cultivars at other sampling points were not significant.

Figure 6.3.2: Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars (Site: Narrabri, 1992/93)



At 674 GDD, l.s.d.$_{(0.05)}$ = 21.04 squares/m^2 At 1245 GDD, l.s.d.$_{(0.01)}$ = 18.3 bolls/m^2
Differences in fruit numbers between cultivars at other sampling points were not significant.

Boll set began at similar dates for both cultivars in 1991/92 and for Siokra 1-4, boll numbers increased earlier and peak boll numbers were reached approximately 200 GDD earlier than Deltapine 90. A similar difference between the cultivars was found in date to peak total fruit numbers. Greater fruit shedding is associated with the okra leaf character of Siokra 1-4 (Thomson, 1986). With the lower fruit retention rate in Siokra 1-4, final boll numbers were not different between cultivars.

In 1992/93 the thermal time (Growing Day Degrees) was less than the long term average during crop establishment and early growth ie. up to 850 GDD. The remainder of the season was optimum for growth and development (Chapter 3.6). The fruiting patterns produced were typical of each cultivar according to historical records (Andries *et al.*, 1969; Gilbert, 1985; Thomson, 1985 and Thomson, 1986).

In the 1992/93 experiment, the date of squaring initiation was identical for each cultivar (Figure 6.3.2). Once squaring was initiated, the rate of squaring in Siokra 1-4 was greater than that of Deltapine 90, reaching peak square numbers at approximately 880 GDD from planting and were 34% greater in number than Deltapine 90. In Siokra 1-4 square numbers declined more rapidly than Deltapine 90, and therefore, Deltapine 90 displayed a more even rate of squaring. Dates to peak square numbers were not able to be differentiated between the two cultivars.

Boll set was initiated at similar dates for the two cultivars again in 1992/93 with boll setting rate initially higher for Siokra 1-4 than Deltapine 90. As peak fruit numbers were reached, the fruit retention rate for Siokra declined more rapidly so that, by later sampling dates, differences in fruit numbers were not different between the cultivars. Although Siokra 1-4 displayed earlier and more rapid flowering rates as described by Andries *et al.* (1969) and Thomson (1985), this did not produce measurable differences in maturity in the 1992/93 season.

Fruiting patterns of Deltapine 90 and Siokra 1-4 following simulated hail damage at four stages of crop development are presented in Figures 6.3.3- 6.3.10.

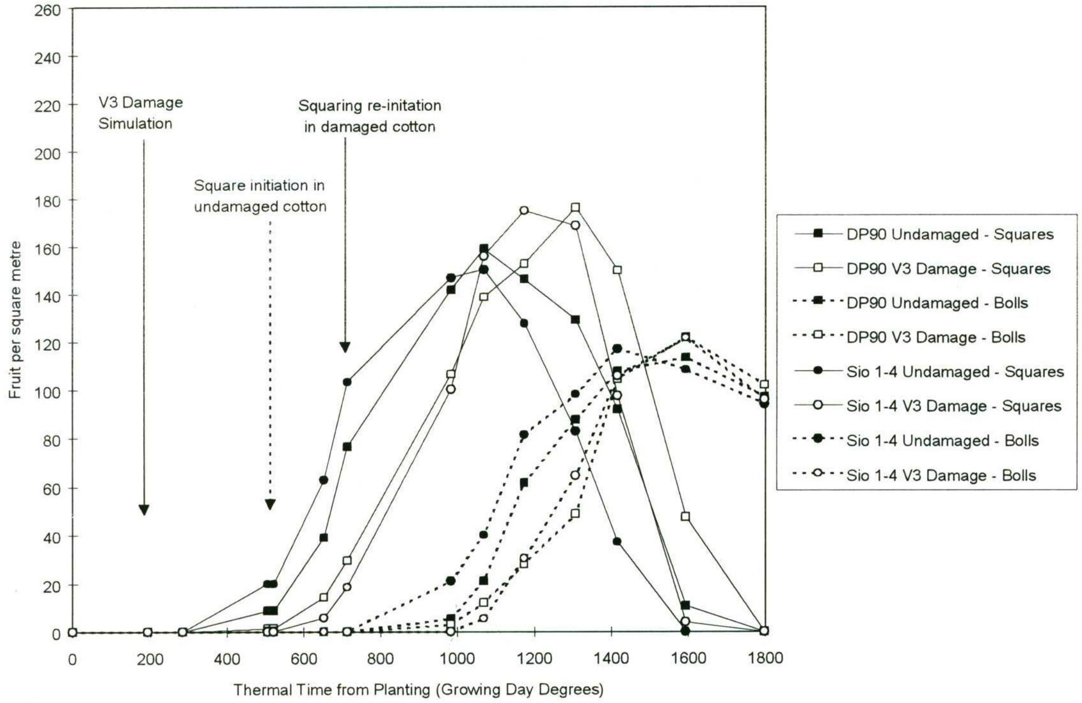
Fruit development following damage in the Vegetative 3 growth stage in the 1991/92 and 1992/93 seasons is presented and compared to development of fruit in undamaged cotton (Figures 6.3.3 and 6.3.4). Following damage simulation at the V3 stage, new squares were not initiated for a period of 450 GDD in 1991/92 and 485 GDD in 1992/93 (Figures 6.3.3 and 6.3.4). I hypothesise that internal repair of plant tissue injured in the damage simulation and initiation of new vegetative and reproductive tissue was occurring in this period, although no change in plant height nor increase in square numbers was measured. Similarly, for cotton damaged by simulated hail at the V5 growth stage, initiation of squaring was at 462 GDD and 426 GDD after damage in 1991/92 and 1992/93, respectively (Figures 6.3.5. and 6.3.6).

Squaring following simulated damage at the R8 growth stage in 1991/92 and R12+ growth stage in 1992/93 showed similar delays (Figures 6.3.7 - 6.3.10). Insufficient sampling points within the period of re-initiation of squaring following simulated damage in the R8 stage in 1992/93 did not allow an accurate estimate of the delay from this treatment. Squaring did not restart following damage in the R12+ growth stage in 1991/92.

Tables 6.3.1 and 6.3.2 summarise squaring initiation dates and re-initiation dates for the cultivars following hail damage simulations. The delay before initiation of squaring following damage was relatively constant across the hail simulation dates used.

The delay before initiation of new fruit combined with the loss in development time imposed by the timing of vegetative damage produced a overall delay in crop development compared to undamaged cotton. ie. crop development is moved later into the season.

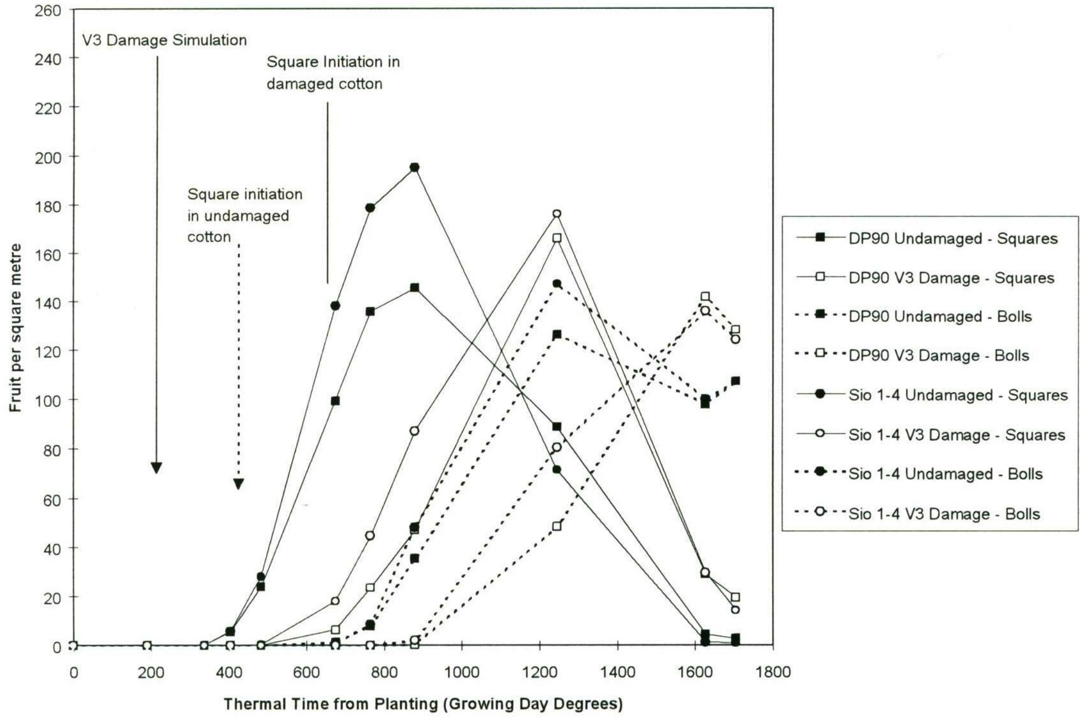
Figure 6.3.3: Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage at the V3 Growth Stage. (Site: Narrabri, 1991/92)



At 652 GDD, l.s.d.$_{(0.05)}$ = 10.1 squares/m^2	At 983 GDD, l.s.d.$_{(0.05)}$ = 6.9 bolls /m^2
At 713 GDD, l.s.d.$_{(0.05)}$ = 13.0 squares/m^2	At 1069 GDD, l.s.d.$_{(0.05)}$ = 10.2 bolls /m^2
At 1593 GDD, l.s.d.$_{(0.05)}$ = 25.6 squares/m^2	At 1307 GDD, l.s.d.$_{(0.05)}$ = 10.4 bolls /m^2
	At 1798 GDD, l.s.d.$_{(0.01)}$ = 15.4 bolls/m^2

Differences in fruit numbers between cultivars were not significantly different at other sampling points.

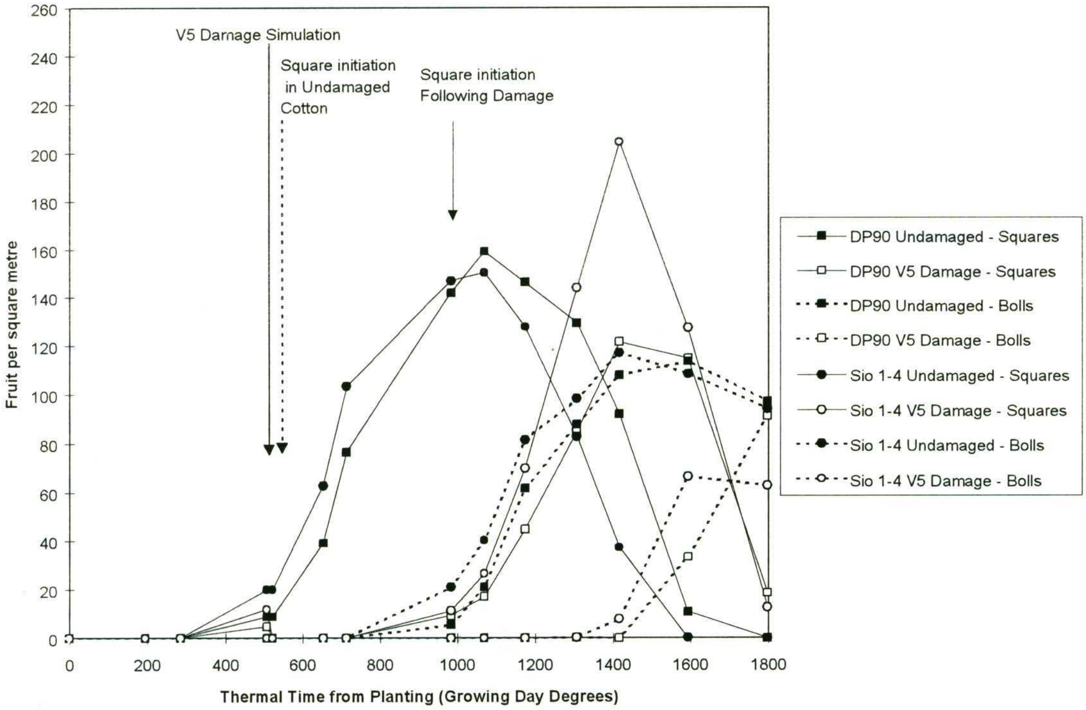
Figure 6.3.4: Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage at the V3 Growth Stage. (Site: Narrabri, 1992/93)



At 674 GDD, l.s.d.$_{(0.05)}$ = 21.0 squares/m^2 At 1245 GDD, l.s.d.$_{(0.01)}$ = 18.4 bolls/m^2

Differences in fruit numbers between cultivars were not significantly different at other sampling points.

Figure 6.3.5: **Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage at the V5 Growth Stage. (Site: Narrabri, 1991/92)**

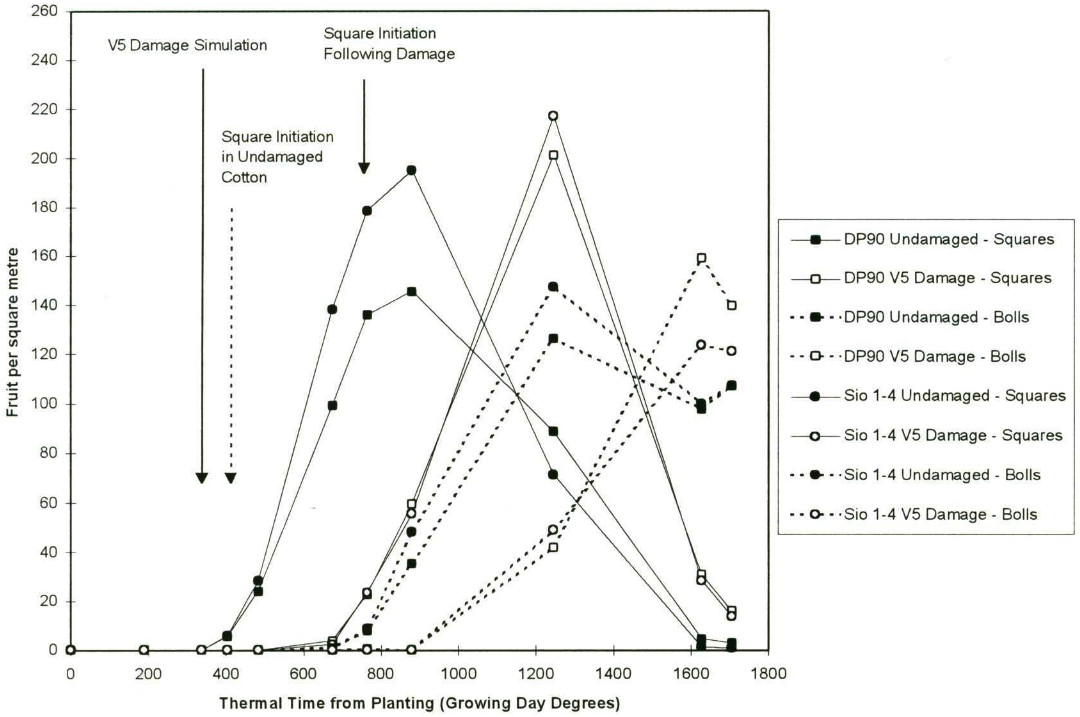


At 652 GDD, l.s.d.$_{(0.05)}$ = 10.1 squares/m^2
At 713 GDD, l.s.d.$_{(0.05)}$ = 13.0 squares/m^2
At 1593 GDD, l.s.d.$_{(0.05)}$ = 25.6 squares/m^2

At 983 GDD, l.s.d.$_{(0.05)}$ = 6.9 bolls /m^2
At 1069 GDD, l.s.d.$_{(0.05)}$ = 10.2 bolls /m^2
At 1307 GDD, l.s.d.$_{(0.05)}$ = 10.4 bolls /m^2
At 1798 GDD, l.s.d.$_{(0.01)}$ = 15.4 bolls/m^2

Differences in fruit numbers between cultivars were not significantly different at other sampling points

Figure 6.3.6: **Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage at the V5 Growth Stage. (Site: Narrabri, 1992/93)**



At 674 GDD, l.s.d.$_{(0.05)}$ = 21.0 squares/m^2

At 1245 GDD, l.s.d.$_{(0.01)}$ = 18.4 bolls/m^2

Differences in fruit numbers between cultivars were not significantly different at other sampling points.

Table 6.3.1: **Initiation of Squaring Following Simulated Hail Damage (Site: Narrabri, 1991/92)**
(From Figures 6.3.2 - 6.3.10)

Growth Stage of Damage	Damage Date (GDD from Planting)	Start of Squaring[1] (GDD from Planting)	Delay in Squaring Compared to Undamaged Cotton (GDD)	GDD to Squaring Following Damage (GDD)
Undamaged	Nil	506	0	0
V3 Damage	203	653	147	450
V5 Damage	521	983	477	462
R8 Damage	1129	1594	-	465
R12+ Damage	1718	-	-	-

[1] Start of squaring defined as being where squares are present at the rate of a minimum of one square per plant.

Table 6.3.2: **Initiation of Squaring Following Simulated Hail Damage (Site: Narrabri, 1992/93)**

Growth Stage of Damage	Damage Date (GDD from Planting)	Start of Squaring (GDD from Planting)	Delay in Squaring Compared to Undamaged Cotton (GDD)	GDD to Squaring Following Damage (GDD)
Undamaged	Nil	404	0	0
V3 Damage	190	675	271	485
V5 Damage	338	764	360	426
R8 Damage	917	1245[a]	-	328[b]
R12+ Damage	1307	1705	-	398

[a] Start of squaring defined as being where squares are present at the rate of a minimum of one square per plant.

[b] Insufficient sampling points for accurate estimate.

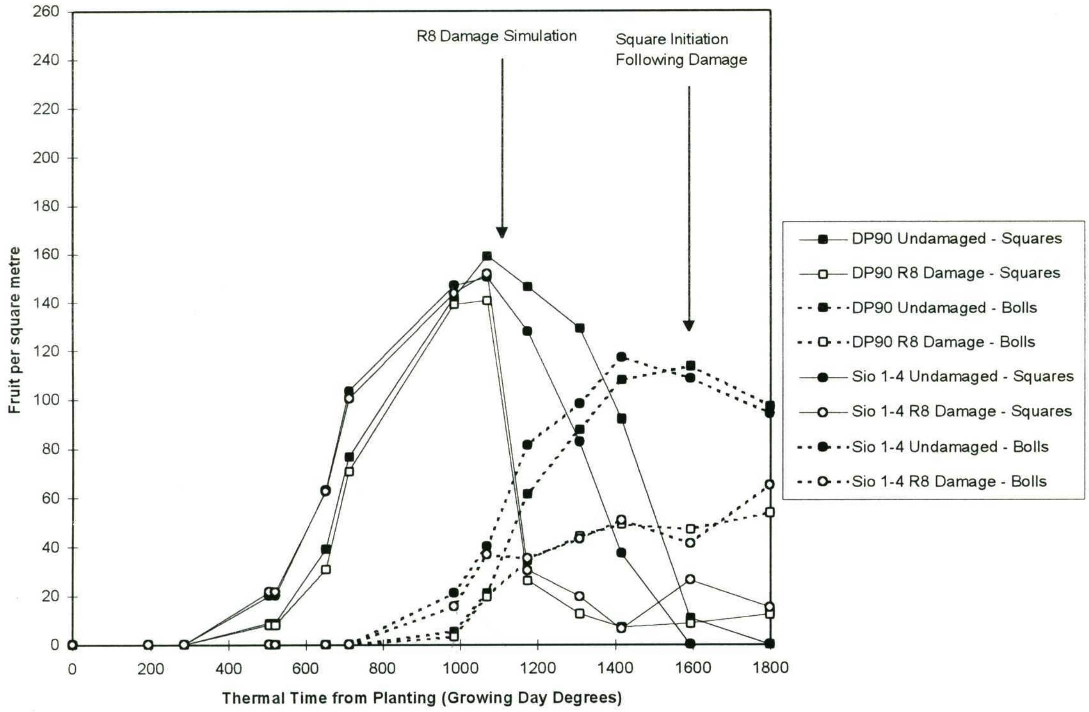
Once fruit development was initiated following simulated damage, fruit development in Siokra 1-4 and Deltapine 90 followed the same patterns as in undamaged cotton (Figures 6.3.3 - 6.3.10). With development delayed, warmer temperatures prevailed and the fruit development curves display the characteristics typical of each cultivar described by Andries *et al.*, 1969; Gilbert, 1985; Thomson, 1985 and Thomson, 1986. ie. Siokra 1-4 squared at a higher rate and reached peak squaring earlier and produced a greater number of squares than Deltapine 90 which squared at a more even rate. Siokra 1-4 in 1991/92 produced greater number of squares compared to Deltapine 90 when developing in the more optimum conditions following simulated damage at the V5 growth stage in 1991/92 ($P < 0.05$). Siokra 1-4 also shed squares and young fruit at a higher rate so that final boll numbers were not different.

Peak square numbers were not reached following V3 stage damage until approximately 200 GDD after undamaged cotton and 300-400 GDD after undamaged cotton following damage in the V5 growth stage. Square initiation increased concurrently with increased vegetative growth following early fruit removal in studies simulating insect damage in cotton (Eaton, 1931; Dunnan, 1943; Dale, 1959; Ehlig, 1969; Evenson, 1969; Wilson, 1972; Malik *et al.*, 1981; Kletter and Wallach; 1982). Increased vegetative growth in terms of plant height has been measured following vegetative stage simulated hail damage in these experiments (Chapter 4.3). Conclusions cannot be drawn in regard to increases in square initiation related to the increased vegetative growth as increases in peak square numbers following vegetative stage simulated hail damage for Siokra 1-4 were not consistent. However, Deltapine 90 displayed 14% and 38% increases in peak square numbers in 1992/93 following V3 and V5 stage simulated hail damage, respectively. Overcast weather conditions which were suggested as acting to depress squaring and fruit retention rates in the 1991/92 experiment and would have affected peak square numbers following vegetative stage damage.

At the R8 growth stage, peak square numbers had already been reached and boll set was increasing. Damage at this growth stage removed most squares and young bolls which were to contribute to overall total final boll numbers (Figures 6.3.7 and 6.3.8). A second fruiting phase was initiated presumably to return the crop to the original full fruit load capacity. Following a 328 - 465 GDD delay after R8 simulated damage (Figures 6.3.7 and 6.3.8), new squares were initiated in both years.

Following damage in the R12+ stage (ie. a mature crop), re-initiation of fruit development was not observed in either cultivar in 1991/92 and limited new squares appeared in 1992/93 (Figure 6.3.9 and 6.3.10). Developing bolls have a priority for assimilates from photosynthesis over vegetative growth and new reproductive growth (Hearn, 1979; Mauney 1979; Mauney, 1986). The boll load remaining after the simulated damage had priority over the re-initiation of squaring and the size of the boll load determined the timing of squaring re-initiation. In both years, irrigation and insecticide application were extended to allow full maturation of regrowth; however no squares initiated on the regrowth following reproductive stage damage matured as bolls due to decreasing temperatures.

Figure 6.3.7: **Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage at the R8 Growth Stage. (Site: Narrabri, 1991/92)**

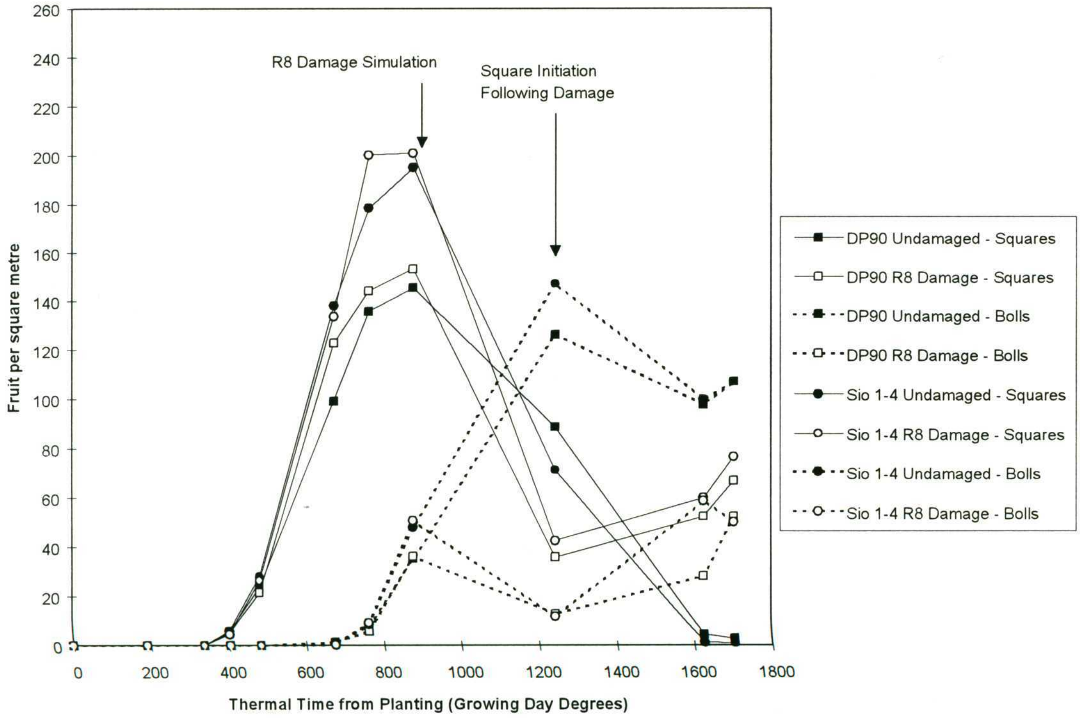


At 652 GDD, l.s.d.$_{(0.05)}$ = 10.1 squares/m^2
At 713 GDD, l.s.d.$_{(0.05)}$ = 13.0 squares/m^2
At 1593 GDD, l.s.d.$_{(0.05)}$ = 25.6 squares/m^2

At 983 GDD, l.s.d.$_{(0.05)}$ = 6.9 bolls /m^2
At 1069 GDD, l.s.d.$_{(0.05)}$ = 10.2 bolls /m^2
At 1307 GDD, l.s.d.$_{(0.05)}$ = 10.4 bolls /m^2
At 1798 GDD, l.s.d.$_{(0.01)}$ = 15.4 bolls/m^2

Differences in fruit numbers between cultivars were not significantly different at other sampling points

Figure 6.3.8: **Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage at the R8 Growth Stage. (Site: Narrabri, 1992/93)**

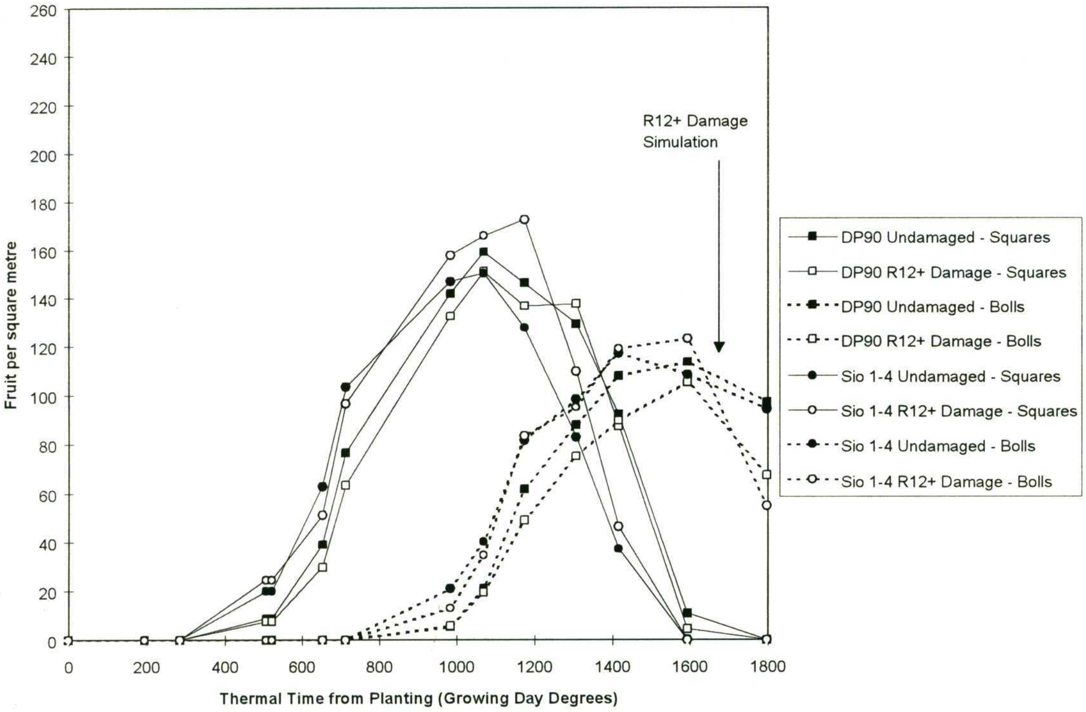


At 674 GDD, l.s.d.$_{(0.05)}$ = 21.0 squares/m^2

At 1245 GDD, l.s.d.$_{(0.01)}$ = 18.4 bolls/m^2

Differences in fruit numbers between cultivars were not significantly different at other sampling points.

Figure 6.3.9: Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage at the R12+ Growth Stage. (Site: Narrabri, 1991/92)

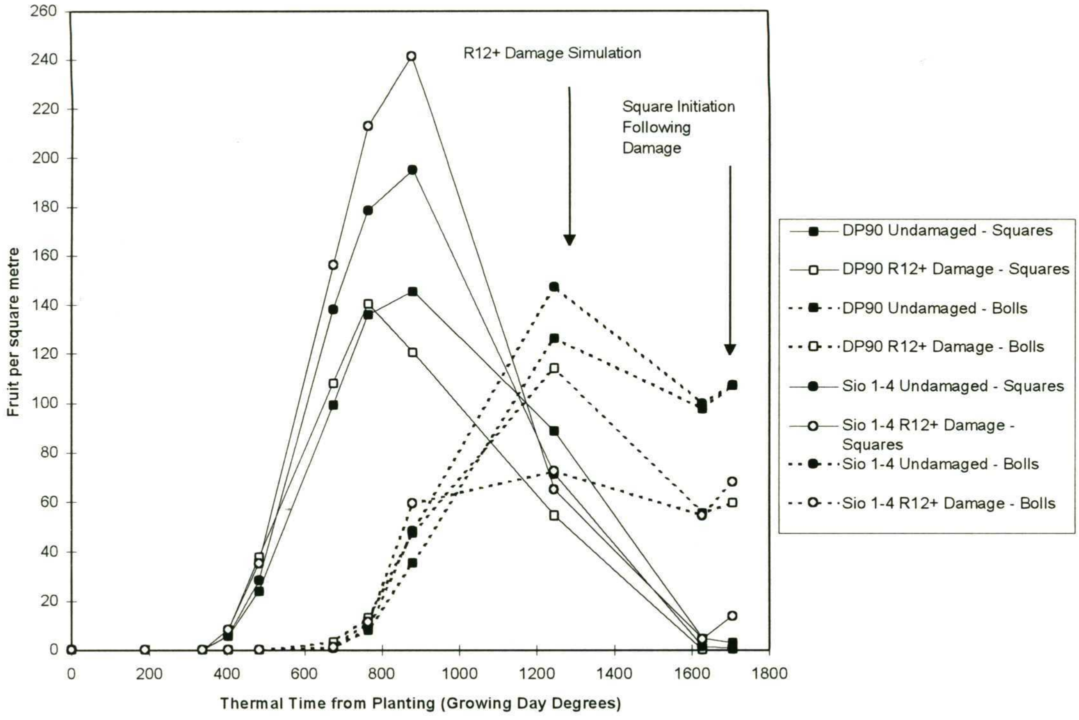


At 652 GDD, l.s.d.$_{(0.05)}$ = 10.1 squares/m^2
At 713 GDD, l.s.d.$_{(0.05)}$ = 13.0 squares/m^2
At 1593 GDD, l.s.d.$_{(0.05)}$ = 25.6 squares/m^2

At 983 GDD, l.s.d.$_{(0.05)}$ = 6.9 bolls /m^2
At 1069 GDD, l.s.d.$_{(0.05)}$ = 10.2 bolls /m^2
At 1307 GDD, l.s.d.$_{(0.05)}$ = 10.4 bolls /m^2
At 1798 GDD, l.s.d.$_{(0.01)}$ = 15.4 bolls/m^2

Differences in fruit numbers between cultivars were not significantly different at other sampling points

Figure 6.3.10: Fruit Development in Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage at the R12+ Growth Stage. (Site: Narrabri, 1992/93)



At 674 GDD, l.s.d.$_{(0.05)}$ = 21.0 squares/m^2

At 1245 GDD, l.s.d.$_{(0.01)}$ = 18.4 bolls/m^2

Differences in fruit numbers between cultivars were not significantly different at other sampling points.

In summary, from the recorded fruiting patterns, I concluded that fruiting patterns of a cultivar following simulated hail damage do not vary from the fruiting patterns of undamaged cotton. The date at which damage is simulated had a dramatic effect on the fruiting response of both cultivars following damage. Damage in the vegetative stages sees a shift in crop development further into the available growing season. Compensatory growth following vegetative damage allows full recovery in terms of fruit development where seasonal conditions are optimal, i.e. when sufficient Growing Day Degrees are available for maturation of regrowth. Damage in the reproductive stages results in little regrowth or re-initiation of fruit development. The reduced compensatory regrowth being due to the remaining boll load having priority for assimilates of photosynthesis and also due to the available Growing Day Degrees being insufficient for the initiation and then maturation of fruit on regrowth.

Chapter 7

Crop Responses in terms of Lint Yield, Crop Maturity and Lint Quality in Cotton Varieties after Damage by Simulated Hail

7.1 Introduction

Varietal differences in the rate of vegetative regrowth after hail damage have been observed in commercial cotton crops in Australia (Cotton Research and Development Corporation, 1990, unpublished). Although Deltapine 90 and Siokra 1-4 cotton cultivars have different patterns of vegetative growth, regrowth of vegetative material after simulated hail damage follows the same pattern as in undamaged cotton (Chapters 4.3 and 5.3). Where damage is inflicted in the vegetative growth stages, vegetative growth is in excess of that of undamaged cotton resulting in a greater final plant height (Chapter 4.3).

The fruiting patterns of a cultivar following simulated hail damage do not vary from the fruiting patterns of undamaged cotton. However, the fruiting response differed with the date at which damage was simulated (Chapter 6.3). Damage in the vegetative stages resulted in a shift in crop development further into the available growing season and full recovery in terms of fruit development occurred provided there was sufficient thermal time (GDD) available for maturation of regrowth. Whereas, damage in the reproductive stages saw little regrowth or re-initiation of fruit development (Chapter 6.3).

It is not known if the increased vegetative growth following vegetative stage damage translates to increased lint yield, or affects crop maturity or lint quality. On the basis of maturity type and fruiting characteristics, Deltapine 90 would be expected to out yield Siokra 1-4 in longer and/or hotter climatic conditions. Siokra 1-4 should yield better than Deltapine 90 in the shorter and cooler cotton production areas. Thomson (1986) produced theoretical yields for Siokra relative to Deltapine 90 for the separate Australian cotton production areas (Table 7.1.1). The Australian Cotton Research Institute situated at Myall Vale, Narrabri would be considered in the Namoi (Wee Waa) district area and hence, lint yields of the two cultivars would not be expected to differ appreciably in the average season.

Deltapine 90 has a fibre of moderate length, high strength and high micronaire and is a highly marketable cultivar in terms of lint quality. In hot long seasons, Deltapine 90 produces a mature fibre with high micronaire, but its micronaire is less stable under cooler conditions or in short seasons (Schulze, 1985). Under these cooler conditions, Siokra 1-4 displays a more stable micronaire and produces mature cotton at lower micronaire values. Lint quality characteristics of the two cultivars are summarised from cultivar trials in Table 7.1.2.

In these experiments, the regrowth of Deltapine 90 and Siokra 1-4 cotton cultivars was monitored following simulated hail at four growth stages. The aim was to determine differences between the cultivars in yield recovery, advances or delays in crop maturity and changes in lint quality induced by simulated hail damage.

Table 7.1.1: **Theoretical Yields of Siokra relative to Deltapine 90 for the Australian Cotton Growing Districts in Three Seasons (ie. As a Percent of Deltapine 90 Yield).**

Source: Thomson (1985).

DISTRICT	**SITE**	**TYPE OF SEASON** **COOL (10% Less Warmth)**	**AVERAGE SEASON**	**HOT (10% Greater Warmth)**
		Yield as % of DP90		
Macquarie Valley	Trangie	119	113	106
	Warren	112	104	97
Namoi/Darling	Breeza	122	115	109
	Wee Waa	111	104	96
	Bourke	103	94	86
Gwydir	Moree	110	102	94
	Collarenebri	108	100	87
MacIntyre / Balonne	Goondiwindi	106	99	90
	St. George	104	96	87
Darling Downs / Lockyer	Brooksted	125	119	113
	Dalby	116	109	102
	Gatton	114	106	99
Central Queensland	Biloela	106	96	90
	Emerald	100	90	82

Table 7.1.2: **Historical Mean Lint Quality Values for Deltapine 90 and Siokra 1-4 Cotton Cultivars.**

Lint Quality Characteristic	**Variety** **Deltapine 90**	**Siokra 1-4**
Length (inches)	1.15	1.18
Strength (grams/tex)	28.50	26.60
Micronaire (micrograms/inch)	4.20	3.90

Source: Variety Trial Handbook - Cotton Seed Distributors Ltd 1993.

7.2 Materials and Methods

Experiments were carried out at the Australian Cotton Research Institute, Narrabri, Australia (149^0 47' E, 30^0 13' S) during the 1991/92 and 1992/93 cotton seasons examining the regrowth of cotton varieties after simulated hail damage. Hail damage was simulated at four plant growth stages during the season as described in Chapter 3.4. Crop management, insecticide and irrigation regimes are described in Appendix 3.1.

Lint yield was determined by sequential hand picking of open cotton for a selected sample area of 1 m^2 per plot at 7-10 day intervals (Constable, 1991). Starting at approximately 20% open bolls in the undamaged cotton (ie. control plots). Weight of seed cotton and number of bolls picked at each date were noted. Sequential picking of seed cotton enabled the percentage of the total lint yield picked at any one picking date to be determined at for each treatment and hence, the average treatment maturity date (Days to 60% Open Bolls) to be calculated for each treatment.

Ginning of seed cotton was carried out at the Australian Cotton Research Institute (A. C. R. I.), Narrabri using a 10-saw experimental gin. Ginning enabled calculation of lint percentages and boll size as defined as weight of lint per boll. Sub-samples of lint were measured for quality characteristics using H. V. I. techniques at the A. C. R. I., Narrabri. Lint quality characteristics and measurement techniques are outlined in Appendix 7.1.

7.3 Results and Discussion

Comparison of Lint Yield, Crop Maturity and Lint Quality between Undamaged Deltapine 90 and Siokra 1-4 Cotton Cultivars.

Lint yields of the two cultivars were the same in each season at the Australian Cotton Research Institute site. The 2-year mean yield of Deltapine 90 was only 18 kg/ha (0.08 ba / ha) greater than Siokra 1-4 (Table 7.3.1).

Table 7.3.1: Lint Yield of Deltapine 90 and Siokra 1-4 Cotton Cultivars

	Deltapine 90		**Siokra 1-4**		
Year	**Yield (kg/ha)**	**Yield (ba/ha)**	**Yield (kg/ha)**	**Yield (ba/ha)**	**Statistical Significance**
1991/92	2637	11.72	2481	11.03	n.s.[1]
1992/93	2430	10.80	2552	11.34	n.s.
2 Year Mean	2534	11.26	2516	11.18	

[1] n.s. = Not statistically significant ($P > 0.05$)

The mean time to maturity (60% Open Bolls) for Siokra 1-4 was 1776 GDD (155 days) from planting (Table 7.3.2). This was an average of 77 GDD (approximately 7 days) earlier to maturity than Deltapine 90. Thomson (1986) noted that Siokra 1-4 exhibited up to 7 days earlier maturity than Deltapine 90 and this was consistent with my experiments.

Deltapine 90, being of Acala origin, possesses a long and strong fibre with high micronaire (Gilbert, 1985). Siokra 1-4 has a slightly lower strength than Deltapine 90 and is lower in micronaire (Table 7.3.3). Lint quality of undamaged cotton in these experiments is presented in Table 7.3.3 and compared to historical values.

Table 7.3.2: **Time to Maturity (60% Open Bolls) of Deltapine 90 and Siokra 1-4 Cotton Cultivars**

Year	Deltapine 90		Siokra 1-4		Statistical Significance
	GDD to Maturity	Days to Maturity	GDD to Maturity	Days to Maturity	
1991/92	1865	156	1770	151	$P < 0.05$
1992/93	1840	163	1782	159	n. s.
2 Year Mean	1853	162	1776	155	

Table 7.3.3: **Lint Quality of Deltapine 90 and Siokra 1-4 Cotton Cultivars**

Variety	DELTAPINE 90			SIOKRA 1-4		
Year	Lint Quality Characteristic			Lint Quality Characteristic		
	Fibre Length (Inches)	Fibre Strength (Grams/tex)	Micronaire (Micrograms /inch)	Fibre Length (Inches)	Fibre Strength (Grams/tex)	Micronaire (Micrograms /inch)
1991/92	1.19	27.28	4.51	1.19	26.47	4.29
1992/93	1.11	28.45	4.62	1.11	27.70	4.42
2 Year Mean	1.15	27.86	4.57	1.15	27.08	4.36
Historical Means[1]	1.15	28.50	4.20	1.18	26.60	3.90

[1] Source: Variety Trial Handbook, Cotton Seed Distributors Ltd., 1993.

N.B.: Differences between measurements of each fibre quality measure were not statistically significant.

Effect of Simulated Hail Damage on Lint Yield of Deltapine 90 and Siokra 1-4 Cotton Cultivars.

Simulated hail damage acted to reduce overall lint yield (Table 7.3.4). At picking, the overall yield loss from simulated hail averaged 64% over the two experiments. The average level of damage inflicted in damage simulations was 59% when assessed at 14 days post damage by N. C. I. S. procedures (Chapters 3.4 and 3.5).

Table 7.3.4: Lint Yield in Undamaged and Simulated Hail Damaged Cotton - Mean of Damage Simulation Dates and Cultivars

	Undamaged Cotton		**Simulated Hail Damaged Cotton**			
Year	**Lint Yield (kg/ha)**	**Lint Yield (ba/ha)**	**Lint Yield (kg/ha)**	**Lint Yield (ba/ha)**	**Statistical Significance**	**l.s.d. (kg/ha)**
1991/92	2559	11.37	1711	7.61	P < 0.001	36
1992/93	2491	11.07	1538	6.83	P < 0.001	54
2-year Mean	2525	11.22	1625	7.20		

Growth stage of the crop at the time of damage was a major contributing factor to the degree of yield loss incurred following simulated damage. Although the overall yield loss inflicted by the simulated damage averaged 59% when assessed by N. C. I. S. methods, the actual yield loss varied depending on the growth stage of the crop at the time of damage (Table 7.3.5). Lint yields for each date of damage were different (P < 0.001). Compensatory growth saw maximum recovery achieved when damage occurred in the vegetative stages.

Table 7.3.5: Lint Yield in Undamaged Cotton and Cotton Damaged by Simulated Hail at Four Crop Growth Stages - Mean of both cultivars

	GROWTH STAGE AT TIME OF DAMAGE										
	CONTROL		V3		V5		R8		R12+		
Year	Lint Yield		Lint Yield		Lint Yield		Lint Yield		Lint Yield		Statistical Significance
	kg/ha	ba/ha	kg/ha	ba/ha	kg/ha	ba/ha	kg/ha	ba/ha	kg/ha	ba/ha	
1991/92	2559	11.37	2699	11.99	1422	6.32	1350	6.00	1375	6.11	$P < 0.001$
1992/93	2491	11.07	2329	10.35	2031	9.03	430	1.91	1362	6.05	$P < 0.001$
2-Year Mean	2525	11.22	2514	11.17	1726	7.67	890	3.92	1368	6.08	

For 1991/92, l.s.d $_{(0.001)}$ = 50.28 kg/ha

For 1992/93, l.s.d.$_{(0.001)}$ = 75.66 kg/ha

Damage was assessed at 59% (averaged over the two experiments) for damage at the early vegetative V3 growth stage. Damage in the V3 growth stage did not consistently produce a reduction in yield (Table 7.3.5). Lint yield was increased by 5.4% over that of undamaged cotton in 1991/92 and decreased by 6.5% in 1992/93. In 1991/92, with early stage crop damage there was sufficient growing season remaining after the damage for the crop to compensate fully. Similarly, full yield recovery is reported following early growth stage defoliation of light-moderate severity by Longer and Oosterhuis (1995). Following early damage, development was delayed and regrowth occurred under warmer temperature conditions than the original development. Given that the rate of development is directly related to temperature (Constable, 1976; Hesketh and Low, 1968; Hearn and Constable, 1984); in 1991/92, with optimum growing conditions following damage, regrowth following V3 stage damage was rapid and combined with an adequate season length, the crop out yielded the undamaged cotton. This did not occur in the following year.

Late vegetative damage at the V5 growth stage on average reduced lint yield compared to undamaged cotton. Lint yield was reduced by 44% in 1991/92 and by 19% in 1992/93 (Table 7.3.5). Yield losses were expected to average 52% according to the N. C. I. S. assessment and hence, again the crop compensated but to a reduced extent compared to damage in the V3 growth stage. The reduced compensation after V5 damage in 1991/92 was related to environmental conditions following the damage. As the damaged cotton attempted to initiate regrowth and squaring, heavy rain occurred in December 1991 and effectively reduced the rate of squaring and peak square numbers. This is in contrast to 1992/93 where conditions were optimum for growth following the V5 damage and a greater yield recovery was achieved.

Damage was assessed according to the N. C. I. S. procedures, at 46% in 1991/92 and 59% in 1992/93 following simulation of damage at the R8 growth stage. Actual losses in yield at picking relative to undamaged cotton were 47% in 1991/92 and 83% in 1992/93 (Table 7.3.5). Simulation of damage at this growth stage was difficult, although removing a set number of main stem nodes, actual fruit removal and foliage removal was estimated and hence, the levels of damage inflicted, as assessed 14 days after the damage simulation, differed between the two seasons. From the fruit development patterns discussed previously (Chapter 6.3), no fruit initiated on regrowth matured to open bolls and hence, regrowth from damage at this growth stage did not contribute to final lint yields.

Cotton at the R12+ growth stage is mature cotton. Losses in yield following hail damage were proportional to the severity of damage inflicted as limited regrowth occurred and there was insufficient growing season remaining for any fruit initiated on the regrowth to mature. In these experiments, lint yields relative to undamaged cotton were 54% and 55% in 1991/92 and 1992/93 respectively. Squares initiated on regrowth in 1992/93 (Section 6.3) did not set as bolls and did not contribute to lint yield.

Damage in the reproductive stages results in a reduction in the ability of a crop to replace lost yield potential. In the reproductive stages, damage removes all squares and immature fruit. Although the cotton plant initiates new vegetative and reproductive growth cycles, the fruit load still present on the plant acts as a stronger sink for assimilates than the new growth. The fruit load still remaining on the plant after damage will be matured before new growth is initiated. When the boll load matures, a new fruiting cycle can be started, but the new fruit initiated only mature and contribute to yield if sufficient heat units are available in the remaining season. Hence, recovery following damage in the reproductive stages in these experiments was inadequate due to the mature growth stage of the crop and insufficient heat units for maturation of any regrowth.

The yield responses of the two cultivars, Deltapine 90 and Siokra 1-4 were similar and were not different for any of the four damage dates in either year (Table 7.3.6). Differences in lint yield between cultivars presented in Table 7.3.6 are not significantly different ($P > 0.05$), ie. Deltapine 90 and Siokra 1-4 cotton cultivars did not respond differently to simulated hail damage.

Table 7.3.6: **Lint Yield of Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Damage by Simulated Hail at Four Growth Stages.**

	Variety			
	Deltapine 90		Siokra 1-4	
	Lint Yield (kg/ha))	Lint Yield (ba/ha)	Lint Yield (kg/ha)	Lint Yield (ba/ha)
SITE: A. C. R. I. - 1991/92				
Undamaged	2637	11.72	2481	11.03
V3	2786	12.38	2611	11.61
V5	1288	5.72	1556	6.92
R8	1308	5.81	1391	6.18
R12+	1287	5.72	1463	6.50
SITE: A. C. R. I. - 1992/93				
Undamaged	2430	10.80	2552	11.34
V3	2105	9.36	2552	11.34
V5	1938	8.61	2123	9.44
R8	440	1.95	421	1.87
R12+	1359	6.04	1365	6.07
A. C. R. I. 2-Year Mean Values				
Undamaged	2534	11.26	2516	11.18
V3	2445	10.87	2582	11.47
V5	1613	7.17	1840	8.18
R8	874	3.88	906	4.03
R12+	1323	5.88	1368	6.08

NB: Differences in lint yield between cultivars were not significantly different.

Effect of Simulated Hail Damage on Time to Maturity of Deltapine 90 and Siokra 1-4.

Time to full maturity is of critical importance in managing the crop to maximise yield recovery and lint quality. Hail damage delayed crop development and crop maturity (ie. time to 60% open bolls) (Table 7.3.7).

In these experiments, hail damage delayed crop development by 138 GDD in 1991/92 overall, and 174 GDD in 1992/93 ($P < 0.001$). This was an effective delay in maturity and therefore a delay in picking of 14-17 days (Table 7.3.7).

Table 7.3.7: **Effect of Simulated Hail Damage on Crop Maturity - Mean of Damage Simulation Dates and Cultivars.**

Year	CROP MATURITY		DELAY TO MATURITY		Statistical Significance
	GDD to 60% Open Bolls	Days to 60% Open Bolls	Delay in GDD	Delay in Days	
UNDAMAGED					
1991/92	1823	156	-	-	
1992/93	1808	161	-	-	
2-Year Mean	1815	158	-	-	
DAMAGED					
1991/92	1960	169	138	14	$P < 0.001$
1992/93	1982	178	174	17	$P < 0.001$
2-Year Mean	1971	173	156	15	

NB: Differences in maturity between damaged cotton and undamaged controls are significantly different in both seasons.

Damage date affected crop maturity. Vegetative stage hail damage simulation (V3 and V5 growth stages) delayed crop maturity in both seasons ($P < 0.001$). V3 stage damage induced a 63-143 GDD (6-13 day) delay in crop development. V5 stage damage resulted in an increased delay in development with maturity delayed by 161-243 GDD or 15-23 days (Table 7.3.8).

Reproductive stage damage simulation had less effect on crop maturity. Crop maturity with R8 stage damage was delayed by only 8 GDD in 1991/92 and 63 GDD in 1992/93 (ie. 1 and 6 days) and hence maturity was not different to undamaged cotton. New squares did not have sufficient heat units available to develop into bolls and therefore time to full maturity was not extended as occurred for damage in the vegetative stages. R12+ stage damage simulation had no effect on maturity in 1991/92 and advanced maturity by 45 GDD or 4 days in 1992/93 compared to undamaged cotton (Table 7.3.8). With damage at R12+, all late formed squares and bolls are removed leaving only mature bolls and hence maturity was advanced compared to undamaged cotton. The delays or advances in maturity of up to approximately 40 GDD measured in these experiments following late reproductive stage damage were not of commercial significance as they did not necessitate major changes in crop or harvest management.

The overall effect of simulated hail damage on the maturity of the two cultivars was similar. The average delay in maturity of Deltapine 90 and Siokra 1-4 induced by simulated hail was 56 GDD (or 6 days) and 68 (or 7 days) respectively (Table 7.3.9). The response in terms of crop maturity for each cultivar, when damaged at different growth stages, was not different ($P > 0.05$) (Table 7.3.10). In 1991/92, damage at the R8 and R12+ growth stages advanced the maturity of Deltapine 90 by 20 and 10 GDD respectively, compared to undamaged cotton. At the same time, the maturity of Siokra 1-4 was delayed by 40 and 20 GDD compared to undamaged cotton when subjected to simulated hail damage at the same growth stages ($P < 0.05$). Differences in maturity of this magnitude are not commercially important.

Table 7.3.8: Comparison of Crop Maturity Following Simulated Hail Damage at Four Growth Stages (Mean of both Cultivars)

Treatment	Year	Crop Maturity		Delay to Maturity		Statistical Significance
		GDD to 60% Open Bolls	Days to 60% Open Bolls	Delay (GDD)	Delay (Days)	
Undamaged	1991/92	1823	156	-	-	
	1992/93	1807	161	-	-	
	2-Year Mean	1815	158	-	-	
V3	1991/92	1885	162	63	6	a
	1992/93	1950	174	143	13	a
	2-Year Mean	1918	168	109	10	
V5	1991/92	2065	179	243	23	b
	1992/93	1968	176	161	15	b
	2-Year Mean	2017	177	202	19	
R8	1991/92	1830	156	8	1	c
	1992/93	1870	167	63	6	c
	2-Year Mean	1850	161	35	3	
R12+	1991/92	1830	156	8	1	c
	1992/93	1763	157	-45	-4	c
	2-Year Mean	1796	157	-19	-2	

Treatments a and b are significantly different each other and treatments c in respective years ($P < 0.01$).

If a delay in development occurs, the cotton crop matures bolls under cooler than optimum temperature conditions. This extends the boll maturation period and could result in reduced lint quality (Mutsaers, 1976). The maturing crop can also be exposed to adverse weather conditions such as rain which not only reduce the quality of lint of open bolls but reduce picking efficiency and hence increase yield loss. Delayed maturity further increases financial losses inflicted by the hail strike.

Table 7.3.9: **Comparison of Crop Maturity of Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage. - Mean of Damage Simulation Dates.**

TREATMENT	YEAR	VARIETY							
		Deltapine 90				Siokra 1-4			
		GDD to 60% Open Bolls	Days to 60% Open Bolls	Delay to Maturity (GDD)	Delay to Maturity (Days)	GDD to 60% Open Bolls	Days to 60% Open Bolls	Delay to Maturity (GDD)	Delay to Maturity (Days)
Undamaged	1991/92	1865	156	-	-	1770	151	-	-
	1992/93	1840	164	-	-	1782	159	-	-
	2-Year Mean	1853	162	-	-	1776	155	-	-
Damaged	1991/92	1910	164	45	5	1823	158	53	7
	1992/93	1908	170	68	6	1865	166	83	7
	2-Year Mean	1909	168	56	6	1844	162	68	7

NB: Differences in maturity between cultivars are not significantly different.

Table 7.3.10: **Comparison of Crop Maturity of Deltapine 90 and Siokra 1-4 Cotton Cultivars Following Simulated Hail Damage at Four Growth Stages.**

GROWTH STAGE AT TIME OF DAMAGE	YEAR	VARIETY							
		Deltapine 90				Siokra 1-4			
		GDD to 60% Open Bolls	Days to 60% Open Bolls	Delay to Maturity (GDD)	Delay to Maturity (Days)	GDD to 60% Open Bolls	Days to 60% Open Bolls	Delay to Maturity (GDD)	Delay to Maturity (Days)
V3	**1991/92**	1935	167	70	7	1842	158	72	7
	1992/93	1965	175	125	12	1915	171	133	12
	2-Year Mean	1950	171	98	9	1879	164	103	9
V5	**1991/92**	2100	182	235	22	2035	177	265	26
	1992/93	1985	178	145	14	1948	174	166	15
	2-Year Mean	2043	180	190	18	1992	175	216	20
R8	**1991/92**	1845	158	-20	-2	1810	154	40	3
	1992/93	1875	167	35	3	1865	166	83	7
	2-Year Mean	1860	162	8	1	1838	160	62	5
R12+	**1991/92**	1855	159	-10	-1	1790	153	20	2
	1992/93	1760	157	-80	-7	1765	157	-17	-2
	2-Year Mean	1808	158	-45	-4	1778	155	2	0

NB: Differences in maturity between cultivars are not significantly different.

Effect of Simulated Hail Damage on Fibre Quality.

The overall effect of simulated hail on fibre quality is summarised in Table 7.3.11. Fibre length was not affected by simulated hail damage ($P > 0.05$). All treatments produced fibre length averages within the acceptable and marketable range (Appendix 7.1). Fibre strength was increased by hail damage in 1991/92 ($P < 0.05$) but not affected in 1992/93. During fibre development, the fibre first lengthens to its final length and then cellulose is laid down to strengthen the fibre (Purseglove, 1974). I hypothesised that a reduction in time available for fibre maturation would reduce fibre strength. However, this was not shown in these results. More importantly, micronaire was reduced on average by simulated hail damage in 1992/93. Reductions in micronaire are of commercial importance as high monetary discounts are imposed for immature fibre.

Table 7.3.11: Effect of Simulated Hail Damage on Lint Quality (Mean of Damage Simulation Dates and Cultivars)

Lint Quality Characteristic	Year	Treatment		Statistical Significance
		Undamaged	Damaged	
Length (inches)	**1991/92**	1.19	1.18	n.s.
	1992/93	1.15	1.16	n.s.
Strength (grams/tex)	**1991/92**	26.87	28.21	*
	1992/93	29.02	29.76	n.s.
Micronaire (micrograms/inch)	**1991/92**	4.40	4.33	n.s.
	1992/93	4.54	4.17	*

* = $P < 0.05$ for comparison of damaged with controls (undamaged).
n.s. = not statistically significantly different.

Quality characteristics are affected differently depending on the growth stage at the time of damage. Table 7.3.12 summarises the effect of damage date on lint quality. Fibre length differences were not different in 1991/92 ($P > 0.05$). However in 1992/93, fibre length was increased by hail damage at each damage date except at the R8 growth stage ($P < 0.001$). No differences were found between dates of damage in respect to fibre strength (Table 7.3.12)

Changes in micronaire with date of damage simulation were only different in 1991/92. Micronaire was reduced by damage in the V5 growth stage compared to damage in the R8 growth stage ($P < 0.05$). Damage at other times and in 1992/93 did not affect micronaire. The large reduction in micronaire in V5 simulated damage plots was primarily due to the fact that damage at this stage caused the longest delay in maturity and bolls were maturing at lower temperatures and a larger proportion of bolls picked were immature and hence of lower micronaire. In R8 stage and R12+ stage simulated hail damage late bolls are removed and so the average micronaire for a lint sample was higher as it represents cotton from mature bolls.

The fact that these experiments were allowed to go through to full maturity with extended irrigations and delayed defoliation encouraged maximum maturity of fibres. Average micronaire values measured following the simulated hail, although reduced by damage, were still within the commercially acceptable range of 3.5 - 4.9 (Appendix 7.1), and hence would not attract a discount in the market place.

Low micronaire indicates fibre immaturity and the presence of finer fibres. In the measurement of fibre strength, a volume of fibres is used and so in measuring the strength of a low micronaire sample eg. hail damaged, more fibres would be used to make up the test sample volume (Appendix 7.1). The strength of such a sample measure high specifically due to the extra strength imparted by the extra fibres rather than a higher strength of individual fibres. Any effect of hail damage on fibre strength would be masked.

Both cultivars reacted similarly after damage in quality terms in 1991/92. Limited cultivar effects were measured in 1992/93 (Appendix 7.2) where Deltapine 90 has an inherently higher fibre micronaire than Siokra 1-4.

In summary, Deltapine 90 and Siokra 1-4 produced similar lint yields at the experimental site. Following simulated hail damage, the cultivars also yielded similarly. The earlier and more rapid initiation of vegetative growth and fruiting did not produce a yield advantage for Siokra 1-4 following damage, nor did the inherent earlier maturity of Siokra 1-4 provide a crop maturity advantage. In respect to lint quality, both cultivars behaved similarly following simulated hail damage. Hence, the inherent differences in vegetative and reproductive growth patterns did not produce differences between the cultivars in yield recovery, advances or delays in crop maturity, nor changes in lint quality following simulated hail damage.

The date of the simulated hail damage was again proven to be the overriding factor determining the degree of recovery achievable (Chapter 4.3, 5.3 and 6.3). Where sufficient heat units remained in the season following vegetative stage damage, although crop development was delayed, almost full yield recovery was possible. Yield recovery was reduced following damage in the reproductive stages where the advanced physiological state of the crop and the reduced available growing season determined that little yield recovery was possible. Related to the delay in crop development following vegetative stage damage was a reduction in fibre micronaire. Lint quality was not affected by damage in the reproductive stages, as the loss of late fruit removed immature bolls which would have reduced the average micronaire of the lint sample.

Table 7.3.12: Effect of Simulated Hail Damage at Four Growth Stages on Lint Quality (Mean of both cultivars)

Lint Quality Characteristic	Year	GROWTH STAGE AT TIME OF DAMAGE					Statistical Significance
		Undamaged	V3	V5	R8	R12+	
Length (inches)	1991/92	1.19	1.19	1.18	1.18	1.19	n.s.
	1992/93	1.15	1.17	1.17	1.12	1.16	***
	2-Year Mean	1.17	1.18	1.18	1.15	1.17	
Strength (grams/tex)	1991/92	26.87	27.27	28.39	27.63	26.86	n.s.
	1992/93	29.02	29.99	30.11	28.75	28.72	n.s.
	2-Year Mean	27.95	28.63	29.25	28.19	27.79	
Micronaire (micrograms/inch)	1991/92	4.40	4.49	4.15	4.50	4.33	*
	1992/93	4.54	4.35	4.06	4.62	4.39	n.s.
	2-Year Mean	4.47	4.42	4.11	4.56	4.36	

*** $P < 0.001$, l.s.d. = 0.05 for comparison of damage date with controls (undamaged)

* $P < 0.05$, l.s.d. = 0.28 for comparison of damage date with controls (undamaged)

Chapter 8

General Discussion

Field observations of the initial vegetative regrowth of cotton cultivars following hail damage reported good recovery in some varieties (Cotton Research and Development Corporation, 1990, unpublished) and provided the impetus for this work examining the response of two cotton cultivars (Siokra 1-4 and Deltapine 90) to simulated hail damage. Yield recovery following hail damage depends on the replacement and maturation of fruit. Hence, this work examined the reproductive development in terms of fruit development, lint yield, crop maturity and lint quality to determine whether inherent differences in fruiting patterns and crop maturity offered any increased yield recovery following simulated hail damage.

These experiments (Figures 4.1.1, 4.1.2, 5.3.1 and 5.3.2) show that vegetative development in both cotton cultivars followed the sigmoid pattern previously described by Marani and Ephrath (1985), Ashley *et al*. (1965), Constable and Gleeson (1977), Mutsaers (1983) and Stern (1964). There were inherent differences between the growth patterns of the cultivars. The initial vegetative development of Siokra 1-4 was more rapid than in Deltapine 90. As Siokra 1-4 moved into the boll setting phase, its rate of vegetative development slowed while Deltapine 90 continued to grow vegetatively and ultimately produced a plant of greater height and leaf area (Figures 4.3.1, 4.3.2, 5.3.1 and 5.3.2). Squaring and boll set initiation dates were similar between cultivars. However, Siokra 1-4 initially squared and set fruit at a greater rate than Deltapine 90. Siokra 1-4 produced a greater number of squares but also shed a large percentage and so final fruit numbers for both cultivars were similar (Figure 6.3.1 and 6.3.2). Lint yields of the two cultivars were similar (Table 7.3.1).

Following simulated hail damage there was a delay before the initiation of regrowth of vegetative material and the initiation of new squares, effectively moving development of damaged cotton later into the available growing season (Figures 4.3.1 - 4.3.10, Tables 5.3.1, 5.3.2 and Figures 6.3.3 - 6.3.10). This delay was relatively constant across the damage simulation dates (Tables 6.3.1, 6.3.2).

Once regrowth was initiated, vegetative and reproductive development followed the same patterns as in undamaged cotton (Figures 4.3.1 - 4.3.10, Figures 5.3.5 - 5.3.8 and Figures 6.3.3 - 6.3.10). Hence, hail damage did not induce changes in the inherent growth patterns of the cultivars. Although Siokra 1-4 was earlier and more rapid in the replacement of vegetative material and fruit initiation, this provided no advantage in increasing the yield recovery of the cotton cultivar compared to Deltapine 90 (Table 7.3.6).

The degree of recovery was determined by the date of the damage simulation. Where damage was inflicted in the vegetative growth stages, crop development was delayed as new growth was initiated and lost plant material replaced; and thus crop development was shifted further into the season (Figures 4.3.1 - 4.3.10, Tables 5.3.1 and 5.3.2). Compensatory growth was greatest with vegetative stage damage where vegetative growth was actually greater than that of undamaged cotton (Figures 4.3.3 - 4.3.8). This produced the largest and most commercially significant delays in crop maturity (Table 7.3.8). In these experiments there was sufficient thermal time (Growing Day Degrees) remaining in each growing season to allow full recovery following vegetative stage damage and completion of the crop development cycles (Table 7.3.5).

In comparison, hail damage simulations in the reproductive stages resulted in a reduced replacement of lost plant material. Limited vegetative regrowth or re-initiation of fruit development occurred and yield recovery was incomplete due to insufficient available heat units. As reproductive stage damage removed a large proportion of squares and late set bolls which acted to extend the time for the crop to reach maturity, crop maturity was either not affected by damage, or was advanced where all late fruit were removed (Table 7.3.8).

The timing of damage rather than cotton variety was the primary factor affecting lint quality. The most significant reductions in micronaire were induced by damage in the vegetative stages where crop maturity delays were greatest and bolls were maturing at lower temperatures and a larger proportion of bolls picked were immature (Table 7.3.12).

The overall regrowth response is, therefore, dependent on (i) growth stage of the crop at the time of damage and hence the growth response that is physiologically possible, and (ii) date of the damage simulation and hence the number of heat units (GDD) that can be accumulated post damage.

The ability to produce compensatory growth following damage is related to the indeterminate growth habit of the cotton plant, its morphological growth pattern and physiological responses to the removal of all or part of the fruit load (Hearn, 1979; Mauney, 1986). The indeterminate growth habit confers unlimited morphological growth. As the main stem develops it produces fruiting branches at successive nodes and an ever increasing number of flower buds are initiated which potentially contribute to lint yield.

Development is only restricted by environmental and physiological factors. As carbohydrate and nitrogen supplies become limiting, competition develops between the various growing plant parts and the nutritional dominance of developing bolls (Hearn, 1979; Mauney, 1986). The rate of morphological development and flower bud initiation, flowering and boll set are reduced and squares are shed. Once the plant has reached the maximum attainable boll load under the available conditions, square production stops (Constable and Hearn, 1984). A second fruiting phase may be initiated as some fruit mature and no longer act as sinks for assimilates (Hearn, 1979). Fruit shedding and the ability to restart morphological development enables the cotton plant to compensate for periods of limited supply of nutrients and water or compensate for loss of fruiting forms due to insect attack or other damage (Guinn, 1982; Hearn, 1979). In this case, compensatory growth occurred following simulated hail damage.

As the crop becomes more physiologically advanced and the crop is carrying a large proportion of the final boll load, the renewal of vegetative or reproductive growth cycles is reduced (Hearn, 1979). With damage in the vegetative growth stages, the crop not only has sufficient heat units available in the season to regrow and mature a large proportion of its original yield potential but its physiological state and lack of fruit load allows for rapid regrowth.

Responses of several crops to hail damage showed that yield recovery after hail was positively correlated with the amount of compensatory growth after damage: the greater the compensatory growth, the lower the yield reduction from the hail damage (Pinto beans, Baldridge, 1971; corn, Hanway, 1969; sunflowers, Johnson, 1972; soybeans, Kalton *et al.*, 1949; cotton, Lane 1959; soybeans, Teigen and Vorst, 1975). My results show that cotton behaves similarly in Australia..

The regrowth responses to hail described are similar to the responses observed following fruit removal or damage by insects. Fruit removal in the vegetative growth stages of cotton development consistently increased vegetative growth and concurrently increased floral bud initiation in simulation of insect damage (Eaton, 1931; Dunnam, 1943; Dale, 1959; Ehlig, 1969; Evenson, 1969; Wilson *et al.*, 1972; Malik *et al.*, 1981; Kletter and Wallach, 1982). I suggest that the increased vegetative growth following vegetative stage simulated hail damage is a similar crop compensation response. In my experiments, increases in peak square numbers corresponding to the increased vegetative growth were measured following vegetative stage damage, but only where squaring was not affected by adverse weather conditions (Figures 6.3.3 - 6.3.6). The removal of early fruiting forms reduced the number of assimilate sinks and allowed the continuation of vegetative development. My conclusion, like Eaton (1931), is that when the nutritional dominance of bolls or fruit was removed, terminal bud and branch development were able to continue.

Compensatory regrowth was reduced following damage in the reproductive stages due to the remaining boll load having priority for assimilates. The available thermal time was insufficient for the initiation and maturation of new fruit. Dale (1959) and Patterson *et al.* (1978) found that in debudding trials, bud formation declines once plants start to set bolls, the presence of a boll load dampened the flowering response and hence, square removal in more mature crops saw a decreased response in terms of square initiation.

This conclusion is further supported by Peoples and Matthews (1981); Kerby *et al.* (1987) viz: removal of first position fruit on a fruiting limb increased the tendency for a boll at second position to be retained and produce more seed cotton than when the first position fruit remained. They also found developing bolls receive assimilates from the bracts and leaves subtending the boll and when bolls are removed from a fruiting limb, assimilates are redistributed, first to other fruit on the limb and then basipetally within the plant. Hence, when fruit remain on a plant following damage, there is a tendency for the weight of the remaining bolls to increase and a decreased tendency for renewed vegetative growth because assimilates are channelled to the remaining bolls and lower plant parts rather than to vegetative apices.

In insect damage simulation experiments, delays in crop development are associated with early defloration and the related increased vegetative growth and increased square production (Wilson, 1972; Ehlig and Le Mert, 1973; Bishop *et al.*, 1977; Wilson and Bishop, 1982; Kletter and Wallach, 1982; Unger *et al.*, 1987). Delayed crop development resulted in yield decreases following defloration when water deficit or climatic restrictions reduced recovery (Dale, 1959; Passlow and Trudgian, 1960; Smith and Varvil, 1981). In the Ord Valley of north west Australia, Evenson (1969) found that early defloration delayed maturity but did not affect yield where the climate did not restrict crop development.

Hail damage delays the maturity of crops by delaying crop development. Moving crop development later into the growing season exposes the crop to deteriorating weather conditions which are not conducive to crop maturation. This delay in maturity may produce problems in harvesting and reduced returns due to immature fibre. A reduction in lint quality (low micronaire) is reported in these experiments (Table 7.3.12) where crop development was delayed to the greatest extent following vegetative stage damage.

Reports on the yield response to removal of fruiting forms in insect simulation work are variable. Early fruit removal increased yields (Eaton, 1931; Hamner, 1941 cited by Dunman *et al.*, 1943; Passlow and Trudgian, 1960; Mistric and Covington, 1968). Yield decreased with early fruit removal when recovery was cut short by water deficit (Dunnam *et al.*, 1943; Evenson, 1969) or temperature restrictions imposed on regrowth in short season areas (Kincade *et al.*, 1970). Yield decreases occurred consistently with later season fruit removal (Dale, 1959; Brown, 1965; Dunnam *et al.*, 1943; Passlow and Trudgian, 1960) and also in my experiments. This is directly related to the heat units remaining following damage. In my experiments, the yield response following damage in the V3 growth stage did not consistently produce a reduction in yield. Lint yield increased by 5.4% in 1991/92 where optimum growing conditions were experienced but decreased by 6.5% in 1992/93. Adverse environmental conditions after damage acted to reduce the regrowth response in 1992/93.

With hindsight, imposition of a damage treatment at approximately the R3 growth stage in these experiments may have been advantageous since a switch in physiology and response was observed between the V5 and R8 growth stages. Damage simulation at approximately the R3 growth stage (early boll fill) may have provided additional information. Due to the rapid growth rate of cotton around the R3 growth stage, it is technically difficult to affect a treatment. Differences in the varietal responses to simulated insect damage in cotton have shown that limiting boll set in the early season induced an greater increase in rate of flower production in more determinate varieties (Patterson *et al.*, 1978). This suggests that fruiting pattern or maturity type may affect the yield response to fruit removal.

Siokra 1-4 is an early, rapid fruiting variety and compensates for early fruit removal to a greater extent than the longer season variety, Deltapine 90, in insect control experiments (Brook *et al.*, 1993a, b, c). This was not the case in my experiments with simulated hail damage. Siokra 1-4 was inherently more rapid in early growth than Deltapine 90 giving the initial impression that Siokra 1-4 was recovering more rapidly from the simulated hail damage. However, no changes in the overall growth pattern, or significant increase or decrease in delay to initiation of regrowth were measured in these experiments. Both cultivars behaved similarly in vegetative development, reproductive development and yield recovery following simulated hail damage.

The degree of yield recovery of a variety or crop depends also on its ability to replace lost vegetative material and replace and mature fruit in the season remaining. Lint yield is directly related to heat unit accumulation (Bilbro and Ray, 1973; Constable, 1976; Constable *et al.*, 1976; Hughes, 1964; McMahon and Low, 1972; Peng *et al.,* 1989). Cool or wet weather conditions towards the end of the growing season or early frosts may bring a premature end to the season thus preventing a hail damaged crop recovering from damage.

In these experiments I have attempted not to disadvantage or restrict the regrowth of either cultivar following damage nor restrict regrowth following damage at any of the damage simulation dates. Irrigations and insecticide application were extended and defoliation delayed to allow full maturation of regrowth in both cultivars and allow maximum recovery following each damage simulation within the climatic limits of the season ie. within the available heat units.

Varietal differences in response to hail damage have been recorded in other crops (Crookston and Hicks, 1977; Crookston and Hicks, 1988; Kalton *et al.*, 1949; Vasilas and Seif, 1985). In these cases environmental conditions eg. end of season drought, have prevented one or more varieties maturing following damage. Smith and Varvil (1984) report increased yield in a short-season cotton cultivar following simulated early-season hail damage. This work was performed in Arkansas, a short season production area, longer season varieties would be disadvantaged by hail damage and the lack of supplementary irrigations would have prevented them reaching full yield recovery potential (Thomson pers. comm.). The length of season differs with cotton production area and so potential recovery from hail differs considerably between cotton production areas. My experiments were carried out in a medium length growing season. The two cultivars in this work did not to differ sufficiently in growth patterns to confer increased recovery from hail damage or a maturity advantage at this site. Cotton varieties displaying more rapid initiation of vegetative material and earlier and rapid fruit set would theoretically be advantageous in shorter or cooler cotton production areas.

Disease susceptibility is another factor which may act after hail damage to increase losses above that assessed at the time of damage. Cotton varieties differ in their susceptibility to diseases such as Bacterial Blight (*Xanthomas campestris* pv *malvacearum*) and Verticillium Wilt (*Verticillium dahliae*). Susceptible varieties may show an increased yield loss after hail due to the development of disease within the crop when weather conditions favouring development of that disease occur. For example, Deltapine 90 is highly susceptible to Bacterial Blight and the open wounds associated with hail damage may provide ideal infection sites in humid or wet conditions. A high incidence of bacterial blight is often observed in hail damaged Deltapine 90 crops. In my experiments, low inoculum levels and dry conditions following simulated damage resulted in negligible infection in Deltapine 90 and no yield reduction due to bacterial blight. A general recommendation should be that growers not plant large areas to disease susceptible varieties if producing their cotton in high hail risk areas.

There are some commercially important points suggested by this work, given the nature of crop responses to simulated hail damage and the contribution that post damage weather conditions, crop management and disease susceptibility can make towards differences between assessed loss and actual yield loss. The loss assessment procedures currently used in cotton hail loss adjustment are applied uniformly across all varieties. By comparing assessed yield losses to actual yield losses measured in these experiments, the accuracy of the loss assessment procedures currently in use could be ascertained. Differences between assessed yield loss and actual loss were similar between the cultivars and as no differences in regrowth were found between the two cultivars, it is appropriate to apply the loss assessment procedures to both cultivar types. However, the procedures may need to be modified before being applied to varieties which have growth patterns widely differing from those examined here.

Loss assessment is carried out 14 days after damage, not at the end of the season. The timing of loss assessment may affect the correlation of assessed yield loss with actual yield loss. There are a number of factors which act post damage to increase or reduce actual yield losses. This is illustrated in these experiments where following simulated damage at the V3 growth stage, damage was assessed at an average of 59% over the two experiments (Tables 3.5.1 and 7.3.5). With compensatory growth, lint yield was totally recovered. Damage was assessed on average at 52% following V5 growth stage damage but at picking, actual lint yields were only reduced by 32% (Table 7.3.5). With optimum weather conditions following damage in the vegetative stages, compensatory growth saw yield losses reduced compared to the yield losses assessed at the time of damage ie. under some conditions yield losses were overestimated.

Following simulation of damage at the R8 growth stage, damage was assessed at an average level of 53%. Actual losses in yield at picking relative to undamaged cotton averaged 65% (Table 7.3.5). The assessment procedures anticipate some degree of regrowth contributing to yield occurring following R8 stage damage. Although some regrowth occurred in these experiments, it did not contribute to yield and hence, the assessment procedures underestimated yield losses due to hail damage at this growth stage. As the assessment of hail damage by commercial procedures may not reflect the actual damage to crops and that hail damage insurance payments may under- or over-estimate the value of crop losses, this work may provide the impetus for the insurance industry to re-evaluate hail damage to crops.

The loss assessment procedures anticipate some compensatory growth following early reproductive stage damage will contribute to yield recovery. In both experiments, regrowth did not contribute to lint yield, hence, the procedures underestimated the yield loss. I suggest they may require adjustment to take into account reduced yield recovery following damage at the early reproductive growth stages.

Yield recovery is reduced when climatic conditions in the later part of the growing season are not conducive to maturation of regrowth. Yield recovery may be further reduced in short season production areas when there are insufficient heat units for maturation of regrowth. Therefore application of the same loss assessment procedures across all crop production areas does not take into account the reduced yield recovery in short season areas. The loss assessment procedures require modification to take into account season length. The basis would be on accumulated thermal time and estimated total thermal time of the season.

Australian cotton breeding programs are in the process of developing cotton cultivars specifically suited for particular production areas eg. short season areas. These cultivars may not only differ significantly in maturity to the cultivars tested but are likely to have widely differing growth patterns which may confer varied recovery from hail damage. The loss assessment procedures may have to be modified to take into account the new variety types.

In conclusion, Deltapine 90 and Siokra 1-4, although having differing parentage and growth patterns, behaved similarly following simulated hail damage; their regrowth pattern did not differ from undamaged cotton, though development was delayed in maturity. This work has shown that date of damage overrides the inherent differences in the growth patterns of the cultivars determining the response of the cultivars in terms of growth and yield recovery following simulated hail damage. Weather conditions after damage, season length, crop management and disease susceptibility have been identified as potential factors contributing to the degree of yield recovery achieved following hail damage.

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Appendix 2.1

Table 2.1.2: Cotton Production in Australia -1993/94

	1993/94 Australian Cotton Production Estimates					
	Irrigated			**Dryland**		
	Hectares	**Yield (Kg/ha)**	**Production (tonnes)**	**Hectares**	**Yield (Kg/ha)**	**Production (Tonnes)**
Queensland						
Emerald	16000	1643	26280	2000	450	900
Biloela/Theodore	4500	1463	6581	1000	315	315
Darling Downs	23000	1238	28463	17000	315	5355
St.George	6000	1620	9720	0	0	0
Total	49500	1440	71044	20000	338	6570
NSW						
Namoi	58000	1553	90045	15000	495	7425
Gwydir	38000	900	34200	12000	270	3240
MacIntyre	22000	900	19800	10000	225	2250
Macquarie	34000	1755	59670	400	563	225
Bourke	9600	1598	15336	0	0	0
Others	7000	1125	7875	0	0	0
Total	168600	1328	226926	37400	360	13140
Australian Total	218100	1373	297970	57400	338	19710

Source: "Cotton Year Book 1994" Edited by D. Dowling, The Australian Cottongrower magazine.

Appendix 2.2

Cotton as a Cultivated Plant - The Lint Bearing Species of the genus *Gossypium.*

Hutchinson *et al*. (1947) classified the species *Gossypium* into eight sections as presented in Table 2.2.1 in Chapter 2, of which sections Herbacea and Hirsuta contain species which bear lint. Hutchinson *et al*. (1947) conclude from cytological studies that the most ancient cultivated cotton is *G. herbaceum* (Section Herbacea). It is the only cultivated species which occurs naturally in the wild, ie. *G. herbaceum* race *africanum*, as found in southern Africa and is considered the most likely species in which the mutation to lint bearing seed occurred (Hutchinson, 1954).

The five races of *G. herbaceum,* races *africanum, acerifolium, wightianum, persicum and kuljianum*, are not agriculturally important. But the second species of Section Herbacea, *G. arboreum*, is the closest species to *G. herbaceum* and is cytogenetically more advanced and considered to have evolved from *G. herbaceum* after the later was brought into cultivation (Hutchinson, 1954). *G. arboreum* race *indicum* is the most closely related to *G. herbaceum* and forms the base of the varieties of cotton of peninsula India. *G. arboreum* races *burmanicum, soudanense, bengalense and sinense* form what is referred to as the Northern Indian Assembly of *G. arboreum*. As cultivated cottons were moved into the northern regions, selection pressure for crops to mature before winter saw annual races develop which now predominate. The annual races of *G. arboreum*, ie. *bengalense* and *sinense*, contribute the bulk of the cotton of northern India and China (Hutchinson, 1954; Purseglove, 1974).

The section Hirsuta contains three species which are all allopolyploids (2n=52) and studies by Skovsted, 1937; Webber, 1939; and Hutchinson *et al.* (1947) have shown that one set of chromosomes are homologous with the Old World or Asian cotton (A genome) probably *G. herbaceum*, and one set homologous with the New World or American wild Species (D genome) possibly *G. raimondii* (Hutchinson, 1954). They are believed to have originated in tropical America although the exact means by which the A genome and D genome species came together to produce the polyploid is widely debated (Skovsted, 1937; Webber, 1939; Hutchinson *et al.*, 1947; Hutchinson, 1954; Thomson, 1975 and Purseglove, 1974. The only general consensus is that the polyploid species evolved in ancient times rather than after a wild species was brought into cultivation.

Of the species of section Hirsuta, *G. barbadense* is found as a wild species of perennial type in the arid mountains of northern Peru. The annual habit was established when seed from the West Indies was introduced into South Carolina in 1786, and gave rise to the high quality 'Sea Island' cotton of the West Indies, crossing of these with other *G. barbadense* cottons produced the very fine annual Egyptian type cottons of the Nile valley. The perennial form of *G. barbadense,* race *brasiliense,* is grown in eastern tropical south America and race *Darwinii* is endemic in the Galapagos Islands. (Purseglove, 1974).

G. tomentosum is a perennial cotton of Section Hirsuta endemic in the Hawaiian Islands, where it grows on arid, rocky or clay plains not far from the sea (Purseglove, 1974).

The third species of the Section Hirsuta and most agriculturally important is *G. hirsutum* which occurs in the wild in perennial and annual forms in central America. The species has evolved in three geographically distinct areas and three morphologically distinct fruiting types or races have developed (Hutchinson *et al.*,1947). The reproductive phase in cotton coincides with dry weather but is initiated by different mechanisms in the three types of *G. hirsutum.*

Race *marie-galante* includes the tallest species cotton ranging up to six metres in height. It is found in back-yard cultivation and sometimes wild in dry coastal areas of Panama, Trinidad and Brazil. The species is highly photoperiodic, flowering only in short days which coincides with the dry season in the Caribbean area. In the perennials, a periodicity is established so that successive crops are produced in the proper season of the year, so that in race *punctatum* fruiting branches may be formed any time but shedding of flower buds occurs in wet weather to ensure flowering is postponed until dry weather. *Punctatum* cottons are found mainly around the Gulf of Mexico (Hutchinson *et al.*, 1947).

Race *latifolium* is annual in habit, with a centre of origin probably Mexico. The ancient stock from central America is not early fruiting and predominantly photoperiodic and may persist for more than one year. But it differs from true perennials in that it produces the bulk of its crop in the first year of growth. When transferred to the southern United States in the eighteenth century forms capable of fruiting irrespective of day length were selected to produce what is now termed the 'Upland' cottons. Upland cottons now form the base of the world's commercial production. With a genetic advantage of yield and quality of lint production the Upland cottons have been transported and cultivated world wide, replacing Asian cultivated species in many cotton production areas (Purseglove, 1974).

Hence, the current cultivated species of cotton have developed from "wild" species of limited distribution in isolated environments. Under selection pressure from man, they have developed to produce high yielding cotton species adapted to a wide range of climatic areas. While the wild species of the genus *Gossypium* provide a diverse germplasm for improvement of the cultivated varieties (Stewart, 1988).

Appendix 2.3

Table 2.3.1. Key to Sections of genus *Gossypium*

Capsule and Seed Hairs	Stem and Leaf Covering	Fruiting Branches	Leaf Lobing	Bracteole Shape and Toothing	Androecium	Section
Capsules with hairs on the sutures, seeds naked or fuzzy, never linted.	Glaucous	2-∞jointed sympodia	Lobed or entire	Ovate entire	-	**I. Sturtiana**
	Glabrous or nearly so, not glaucous	Jointed peduncles or flowering spurs	Entire or nearly so	Reduced, or ovate and caducous	-	**II. Erioxyla**
	Hairy	2-∞jointed sympodia	Entire	Many toothed	-	**III. Klotzschiana**
	Glabrous or nearly so, not glaucous.	∞- jointed sympodia	Lobed	Entire or 3-toothed, sometimes reduced.	-	**IV. Thurberana**
	Hairy	Jointed peduncles or 2-∞jointed sympodia	Lobed	Linear, usually 3-toothed.	-	**V. Anomala**
	Hairy or nearly glabrous	2-∞jointed sympodia	Usually lobed (Rarely with both leaves and bracteoles entire)	Usually gashed or serrate.	-	**VI. Stocksiana**
Capsules without hairs on the sutures, seeds linted	Variously hairy or nearly glabrous, not glaucous	∞- jointed	Lobed	Entire, coarsely toothed or serrate, teeth rarely thrice as long as broad.	Anther filaments short, all about the same length.	**VII. Herbacea**
					Anther filaments long, upper ones longer than the lower.	***G. tomentosum* in VIII. Hirsuta.**
				Coarsely toothed or serrate, teeth more than thrice as long as broad.	-	**VIII. Hirsuta**

Source: Hutchinson *et al*. (1947)

Appendix 2.4

Hormones in Cotton Physiology

The role of plant hormones in the early development of cotton and the initiation of flowering has not been studied in great detail. But as most of the cultivated cottons are day neutral, flowering initiation is self-inductive (Guinn, 1986). Once the cotton plant starts flowering it usually continues to do so until cut out with fruit set regulated by shedding. Guinn (1986) suggests that morphological development slows and eventually ceases in response to increasing boll load and that plant hormones have a key part to play in the regulation of growth and fruit abscission. The role of plant hormones in fruiting of cotton has been reviewed by Hearn and Constable (1984) and Guinn (1986).

The various plant hormones interact in the abscission process of shedding. Hearn and Constable (1984) postulate that the mechanism for fruit abscission in cotton is actually concerned with relative levels of auxins, ethylene and abscisic acid (ABA) in the fruit.

Pectinase and cellulase are synthesised within the plasmalemma and are secreted and move to the site of action in the middle lamella and primary cell wall, where they digest the middle lamellae and soften portions of the cell walls in the abscission zone and therefore weaken the peduncle allowing for fruit shedding (Yager, 1960, and Moree, 1968 cited by Guinn, 1986). Ethylene and abscisic acid (ABA) are found to be produced in large amounts in bolls during shedding and dehiscence and promote the synthesis of pectinase and cellulase in the abscission layer (Smith, 1969, and Davis and Addicott, 1972 cited by Hearn and Constable, 1984).

Ethylene acts to slow the transport and increase destruction of auxin in the plant (Beyer, 1973 and Davenport, 1976 cited by Hearn and Constable, 1984). Guinn (1986) cites work by Morgan and Hall (1962), Hall and Morgan (1964), and Morgan *et al.* (1968) showing that ethylene stimulates IAA-oxidase activity and decarboxylation of IAA in cotton and that ethylene slows the transport of the auxin and hence, acts to promote abscission. Although, ethylene is found in all parts of the plants, it is produced in low levels early in the season when abscission rates are low, then production increases through the season and between irrigations as boll abscission rates increased ie. as nutrient competition and water deficits increase (Guinn, 1986). Low light and wounding were also found to increase ethylene production (Guinn, 1982a, cited by Guinn, 1986) and therefore explains the increase in fruit shedding in cotton under overcast weather conditions.

Abscisic acid (ABA) acts in a similar manner to ethylene in hastening senescence, decreasing the basipetal movement of auxin, and by promoting the production of ethylene and an increase in cellulase activity. ABA is found in large quantities in bolls during shedding and dehiscence (Smith, 1969; Davis and Addicott, 1972 cited by Hearn and Constable, 1984).

Auxins act indirectly to inhibit abscission by maintaining the flow of assimilates to the fruit and act directly by suppressing the synthesis of cellulase (Abeles, 1969). This is supported by the fact that more auxin is found in retained bolls than ones about to be shed (Varma, 1978 cited by Hearn and Constable, 1984). Hearn and Constable (1984) suggest that auxins generally maintain ongoing physiological processes such as stimulation of cell elongation, enhancement of RNA and protein synthesis, maintenance of differential permeability of membranes, and increase assimilate mobilisation, and hence, the presence of auxins in a fruiting body makes it a stronger sink for attracting assimilates.

Fruit that are adequately supplied with nutrients grow normally and produce auxin which inhibit the production of the enzymes in the abscission layer and counteract the effects of ethylene and ABA. On the other hand, fruit inadequately supplied with nutrients grow slowly or not at all and consequently produce less auxin. The amount of auxin is insufficient to counteract the effect of ethylene and ABA in promoting the synthesis of enzymes and an abscission layer develops (Hearn and Constable, 1984).

Hearn and Constable (1984) note that older fruit do not shed, although auxin production declined, as well as ethylene and ABA production. If stress causes an abscission layer to develop, the boll does not shed because of secondary thickening of the vascular bundles, the boll will dry out *in situ* and become mummified. Morris (1964) cited by Hearn and Constable (1984) found that the formation of an abscission layer occurs in all bolls as the fruit matures and growth stops, but the bolls do not drop because of secondary thickening, they dry, split and open along the preformed sutures.

Gibberellins and cytokinins are also associated with fruit shedding. Guinn (1986) suggests that gibberellins act to inhibit abscission by promoting the movement of nutrients to the fruit and stimulating growth and promote the synthesis of auxins, as gibberellins are produced by most growing parts of plant and in particular developing seeds. This is supported by the findings of Bjardwaj *et al.* (1975) and Varma (1976a) cited by Hearn and Constable (1984), that application of gibberellic acid to bolls decreased boll shedding but increased square shedding.

Cytokinins are synthesised in root tips and are active in the maintenance of ongoing processes and nutrient mobilisation in the tops of plants, inhibiting abscission by stimulating auxin production. Peak cytokinin production in bolls is 4-9 days after flowering after which it declines (Sandstedt, 1971 cited by Hearn and Constable, 1984). Guinn (1986) describes cytokinins as senescence retardants through their promotion of RNA, protein and lipid synthesis and their role in promotion of transport of metabolites and hence working to maintain protein and nucleic acid levels.

Appendix 2.5.1

Irrigation Scheduling in Cotton

Irrigation scheduling has now developed to a more scientific and accurate level.

The use of neutron probes to predict irrigation dates is common in Australia and assumes that the moisture content at permanent wilting point of the soil under study, and the amount of water required to bring such a soil a soil back to field capacity is pre-determined. The difference between the two values is the water available to the plant. The refill point when irrigation is required is established, and relates to the moisture level below which the crop will be stressed (Figure 2.5.3). Regular soil moisture readings by neutron probe are then used to predict the date at which the refill point is reached and irrigation is due (Cull, 1980).

Figure 2.5.3: Example of a Soil Moisture Profile for Cotton in the Namoi Valley of N.S.W., Australia.
Source: Browne (1984)

The pressure chamber technique is an objective measure of leaf water tension. As the soil moisture level declines during an irrigation cycle, the plant experiences increasing water deficit or tension which eventually affects growth and yield. Optimum growth is occurring with mid-day LWP values in range of -1.6 to -1.7 Mpa and once values drop below this level deficit as determined by pressure chamber values, irrigation is required (Browne, 1984).

The use of canopy temperature measurements has been proposed for use in irrigation scheduling and is based on the fact that in the process of transpiration, water is evaporated from the surface of the plant and hence the leaf surface temperature is lower. An actively transpiring crop has a lower canopy temperature than an equivalent crop which is approaching water stress and hence is beginning to transpire less actively. Infra-red technology for measuring canopy temperature has not yet been widely adopted (Hearn, 1995).

Appendix 2.5.2

Defoliation, Harvesting and Ginning of Cotton

In more developed large scale cotton production mechanical harvesting is normal. Spindle pickers are used to pick most of the Australian crop. The harvesting mechanism consists of rows of revolving vertically-mounted, tapered and barbed spindles. As the machine passes through the crop, seed cotton is dragged or lifted from the open bolls by the spindles and drawn by air vacuum up through shutes to the picker basket. In modern systems, seed cotton is dumped from the picker basket into module builders, which are basically large presses which consolidate the cotton into large blocks for transport to the gins by road transport. Prior to the development of module builders, seed cotton was transferred from the picker to wire trailers and transported to the gin. The advent of modules has allowed a much larger bulk of seed cotton to be transported in one movement. Stripper type pickers which harvest seed cotton and dried leaf are used on some dry land crops to harvest all seed cotton present, but growers suffer discounted returns due to excess leaf trash and debris.

Spindle picking requires the cotton plant at picking to be largely free of leaf material for the efficient operation of the pickers. Hence, defoliation of the crop is practiced which increases the percentage of seed cotton picked and improves the quality of the lint by lowering the trash content and green stain. By defoliating as soon as all pickable bolls are mature, boll opening rate is increased (Cardozier, 1957). Hence, crops are usually defoliated when 60-70% open (Thomson, 1975). Chemicals are used to apply an injury or artificial stress to the plant and induce leaf drop and desiccation. Chemicals currently used for defoliation include Dimethipin (Harvade), Thidiazuron (Dropp), Magnesium Chlorate (Magsol) and Sodium Chlorate (Leafex and Atlacide). Ethephon (Prep) is used to promote boll opening. Other chemicals increase the efficacy of defoliants in adverse conditions eg. Endothal (Accelerate) is used to increase the rate of leaf drop, while Oleyl Alcohol (Catapult), Paraquat and Diquat are used as surfactants (Shaw, 1994).

Harvested seed cotton contains 35-40% cotton lint fibre and the rest is seed and debris from the plant. Ginning separates the lint fibres from the seed. Prior to ginning seed cotton is dried to a moisture content of approximately 6%, hot air is used to remove leaf trash and dirt. The actual cotton gin consists of a series of circular saws rotating at high speed and set in encircling steel ribs. Seed cotton is fed to the gin, fibres are drawn through the ribs and the seed is cut or torn away by the saws. The lint fibres are drawn away by high speed brushes and further cleaned by combing and then pressed and packed into 227 kilogram bales. Cotton seed is used for processing to produce cotton seed oil and meal, or can be used for stockfeed (Thomson, 1975; Australian Cotton Foundation, 1990).

Appendix 3.1: Crop Management

Table 3.6.3: Crop Management - Australian Cotton Research Institute (Field 3) 1991/92

Effective Planting Date	9/10/91
Average Plant Stand Established	9.1 Plants/metre^2
Planting Bed Width	1 metre
Irrigation Method	Furrow

Ground Preparation

Date	Operation
2/11/90	Disc Plough
5/02/91	Chisel Plough
19/02/91	Furrowing out
6/08/91	Sledge rig x 2
22/08/91	Lillistons
19/09/91	Roller
13/11/91	Lillistons

Fertilisers

Date	Type	Rate
12/08/91	Anhydrous Ammonia	100 NH_3 kg/ha

Herbicides

Date	Type	Rate	Active Constituent
22/08/92	Stomp	3 litres/ha	Pendimethalin
10/10/92	Cotoran	4 litres/ha	Fluometuron

Insecticides

Date	Type	Rate	Active Constituent
5/11/91	Rogor	0.5 litres/ha	Dimethoate
21/11/91	Endosulfan EC	2.2 litres/ha	Endosulfan
5/12/91	Thiodan	2.1 litres/ha	Endosulfan
	Rogor	0.5 litres/ha	Dimethoate
23/12/91	Endosulfan EC	2.2 litres/ha	Endosulfan
	Rogor	0.5 litres/ha	Dimethoate
9/01/92	Karate EC	0.4 litres/ha	Lambdacyhalothrin
	Comite	2.5 litres/ha	Propargite
31/01/92	Endosulfan EC	2.2 litres/ha	Endosulfan
7/02/92	Comite	2.5 litres/ha	Propargite
	Karate EC	0.4 litres/ha	Lambdacyhalothrin
28/02/92	Curacron EC	1.75 litres/ha	Profenofos

Irrigations

Pre-irrigation:	1/10/91
Crop irrigations:	22/10/92
	2/01/92
	13/01/92
	23/01/92
	31/01/92
	21/02/92
	11/03/92

Defoliation	29/04/92	**Commercial Pick**	25/05/92

Table 3.6.4: Crop Management - Australian Cotton Research Institute (Field 5) 1992/93

Effective Planting Date 12/10/92
Average Plant Stand Established 10.9 Plants/metre
Planting Bed Width 1 metre **Irrigation Method** Furrow

Ground Preparation

Date	Operation
19/02/92	Disc Plough
2/03/92	Chisel Plough
4/03/92	Chisel Plough
9/03/92	Disc Plough
11/03/92	Furrowing out
19/06/92	Go-devil
24/08/92	Lilliston

Fertilisers

Date	**Type**	**Rate**
3/07/92	Anhydrous Ammonia	138 NH_3 kg/ha

Herbicides

Date	**Type**	**Rate**	**Active Constituent**
24/08/92	Stomp	3 litres/ha	Pendimethalin
12/10/92	Cotoran	2 litres/ha	Fluometuron

Insecticides

Date	**Type**	**Rate**	**Active Constituent**
18/12/92	Endosulfan EC	2.2 litres/ha	Endosulfan
	Rogor	0.5 litres/ha	Dimethoate
4/01/93	Endosulfan EC	2.2 litres/ha	Endosulfan
	Rogor	0.5 litres/ha	Dimethoate
15/01/93	Karate EC	0.4 litres/ha	Lambdacyhalothrin
25/01/93	Endosulfan EC	2.2 litres/ha	Dimethoate
	Dipel ES	1.5 litres/ha	*Bacillus thuringiensis*
2/02/93	Karate EC	0.36 litres/ha	Lambdacyhalothrin
	Comite	2.5 litres/ha	Propargite
18/02/93	Larvin 375	2.0 litres/ha	Thiodicarb
26/02/93	Rogor	0.5 litres/ha	Dimethoate
5/03/93	Comite	2.5 litres/ha	Propargite
26/03/93	Rogor	0.5 litres/ha	Dimethoate

Irrigations

Pre-irrigation:	18/09/92
Crop irrigations:	21/12/92
	7/01/93
	15/01/93
	25/01/93
	8/02/93
	16/02/93
	8/03/93

Defoliation 26/03/93 **Commercial Pick** 23/04/93

Appendix 7.1:

Lint Quality Measurement

Lint quality of samples was determined by the C. S. I. R. O. Cotton laboratory at the Australian Cotton Research Institute, Narrabri. Results are produced by Spinlab (Zellweger Uster) high volume instrument (H.V.I.).

Length: Unit of Measure - Inches

Scale of Value -

<	1.00	Very Short
1.00 -	1.14	Medium
1.15 -	1.29	Long
>	1.29	Extra Long

Principle of Operation - Mass of the beard is determined optically by measuring light absorption. Density readings are converted by software into a fibrogram from which length values are extracted.

Strength or Tenacity (grams/tex):

Fibre strength has become increasingly important as faster spinning methods produce weaker yarn. The fibrocomb holding the beard is moved automatically into the instrument a second time following the length test.

< 24	Very Low
24 -26	Low
27- 30	Average
31-34	High
> 34	Very High

Micronaire (micrograms per inch): 3.5 to 5.0 accepted without penalty

Appendix 7.2:

Table 7.3.13: Effect of Simulated Hail Damage at Four Growth Stages on Lint Quality of Deltapine 90 and Siokra 1-4 Cotton Varieties.

		Variety					
		Deltapine 90			Siokra 1-4		
Growth Stage at Time of Damage	**Experiment**	**Length (inches)**	**Strength (grams/tex)**	**Micronaire (micrograms /inch)**	**Length (inches)**	**Strength (grams/tex)**	**Micronaire (micrograms /inch)**
V3	**1991/92**	1.19	27.35	4.68	1.19	27.20	4.30
	1992/93	1.15	29.90	4.15	1.20	30.08	4.55
	2-Year Mean	1.17	28.63	4.41	1.20	28.64	4.43
V5	**1991/92**	1.17	29.10	4.14	1.18	27.68	4.16
	1992/93	1.14	29.91	3.98	1.21	30.30	4.15
	2-Year Mean	1.15	29.51	4.06	1.20	28.99	4.16
R8	**1991/92**	1.15	27.96	4.63	1.21	27.30	4.38
	1992/93	1.09	28.79	4.83	1.15	28.71	4.41
	2-Year Mean	1.13	28.38	4.73	1.18	28.01	4.40
R12+	**1991/92**	1.19	26.96	4.51	1.19	26.76	4.15
	1992/93	1.14	28.06	4.70	1.17	29.37	4.07
	2-Year Mean	1.17	27.51	4.61	1.18	28.07	4.11