Compensation in cotton following pest damage: potential and limitations

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Abstract

Damage caused by chewing and sucking pests does not necessarily lead to a yield loss in cotton. There is ample evidence indicating that cotton can fully recover from levels of vegetative and fruit damage above the current industry threshold. The ability to compensate for tissue loss in cotton is attributed to an improved canopy development stimulated by pre-squaring tip damage, and to fruit substitution for damage and increased fruit production during the reproductive stage. However, cotton's ability to compensate for fruit loss declines dramatically as boll development accelerates (3-4 weeks after first square), therefore, a more cautious pest management is necessary for about 2 months (until cut-out) to avoid yield loss. A look-up table of the estimated fruit damage caused by *Helicoverpa* larvae at different fruiting stages is provided to allow assessment of a crop's ability to tolerate fruit loss. To ensure full compensation, it is important to maintain a healthy crop canopy (i.e., keeping mite damage under control) but not one with excessive leaf area (which leads to yield loss), particularly during the boll forming stage. Excessive growth response to pest damage may be minimised by selecting okra leaf cultivars and by managing nitrogen and irrigation properly. A well managed crop may even respond to damage such as early season tipping out with yield gain over an undamaged crop. Clearly, the potential for reduced pesticide use in early and mid-season clearly exists and so do the attendant benefits of that. Harnessing the compensatory capacity of cotton is a key component of Integrated Pest Management and sustainable cotton cropping. This research continues the effort to ascertain ways of fully utilising the compensation potential of cotton for future incorporation into decision support systems for pest management.

Why is compensation important?

"It will become increasingly rare for farmers to use pesticides when the damage is not of economic importance" Wilson (1986). This observation has taken on a greater imperative in the current cotton cropping system in Australia. Knowing the full capacity of a cotton crop to recover from pest damage means we can raise the threshold for *Helicoverpa* and other pests without suffering economic penalty. Moreover, there are important benefits to reducing pesticide use:

- reduced cost
- less impact on the environmental
- slow the development of insect resistance
- encourage beneficial arthropods
- minimise flaring of secondary pests
- possible yield gain

While the introduction of transgenic cotton represents a significant advance in cotton pest management, compensation remains important. The current Bt cottons do not protect the crop throughout the season and even with the forthcoming 2-gene lines, non-lepidopteran pests remain a threat. Given that different cultivars have different sensitivities and recovery patterns to pest damage, the key question is at what level would pest damage become "economically important"? Of equal importance is the question of how compensation varies under different agronomic conditions and in different cropping regions. Information from this study can help us to develop guidelines for pest management which take full advantage of the compensation capacity of cotton.

How tolerant is cotton to damage?

As early as the 1930s, cotton researchers had begun to assess the tolerance of cotton plants to pest damage (e.g., Eaton, 1931). Since then, a substantial number of studies have found full or over- compensation of yield in crops even after fairly heavy damage to leaves, terminals and fruit. Sadras (1995) presented a review of the evidence supporting the case that damage episodes at levels above the current threshold do not necessarily reduce yield. In our own field trials in the last two years, we simulated more realistic damage by imposing multiple damage events including both pre-squaring tip damage and fruit removal. We also used several levels of artificial pest damage ranging from no additional damage to 8 larvae per metre (Fig. 1). The results of the two-year trial demonstrate two key points. Firstly, cotton can compensate from repeated damage at levels as high as 8 *Helicoverpa* larvae per metre without significant yield loss (note that histograms in Fig. 1 have a break which accentuates the differences among treatments). Secondly, even though the yield potential may have differed considerably (Yr 2 was twice that of Yr 1), the ability to compensate was not strongly affected.

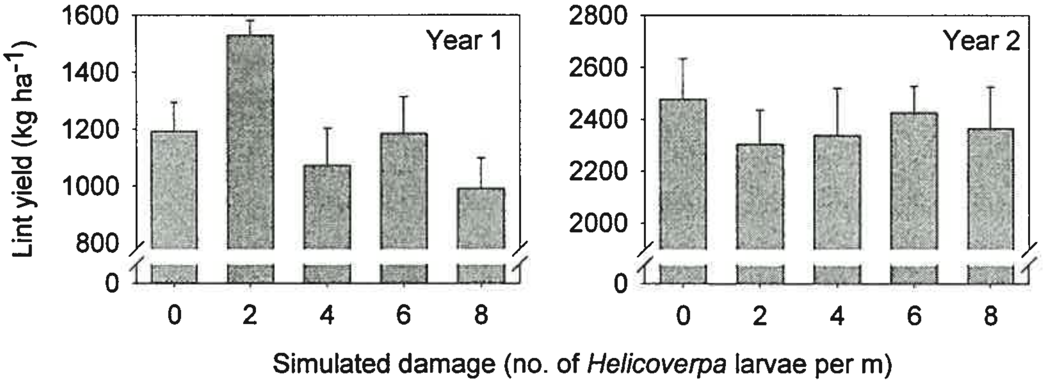

Figure 1. A two-year field trial conducted at Narrabri examining the ability of cotton to compensate from repeated damage simulating 0-8 *Helicoverpa* larvae per metre. The damage imposed consisted of two tip damage events before first square (80% of plants tipped out) and 2 fruit removal events (last event was about 130 DAS). Sicala V2 (Yr 1) and Sicala V2i (Yr 2) were grown using standard N and irrigation management and plant stand at 10 plants per metre. The number of fruit removed for each simulated larval level was calculated using actual fruit count and the *Helicoverpa* Feeding model (see Table 1), fruit were removed in a random fashion by hand.

How does cotton recover from damage?

Cotton plants respond to different types of pest damage in different ways. Early season tip damage induces a strong response for lateral branch growth. We will look at this more closely later. When leaf area is reduced either by defoliation or through mite infestation, the plant experiences reduced vegetative growth and fruit development. Moderate levels of leaf loss may not have an economic effect on yield (see below). Loss of fruit can lead to an increase in vegetative or reproductive growth depending on the number of fruit remaining on the plant. If there is a sufficient number of fruit remaining, then substitution of lost fruit can maintain the carbon demand by fruit without resuming vegetative growth. If few fruit remain, then the surplus carbon will be used for a spurt of vegetative growth until fruit numbers build up again. In the later case, because fruit development is temporarily interrupted, there may be a delay in boll maturation.

Structural changes resulting from tip damage or reduced leaf area

When early season pests damage the terminal of a young cotton plant, the plant is stimulated to produce lateral branches from main stem leaf nodes below the terminal. The number and position of lateral branches produced differs between cultivars and may be related to their degree of apical dominance (Sadras and Fitt, 1997). Figure 2 shows a significant increase in the number of branches produced from manual tip damage prior to squaring. With the development of lateral branches, the cotton canopy usually becomes more efficient in intercepting light and therefore could accumulate more carbon. More branches also means more potential fruiting sites and a larger square production. Since plants with more fruit can tolerate more damage (through substitution of lost fruit), we believe tip damage could also help cotton to resist fruit damage later in the season.

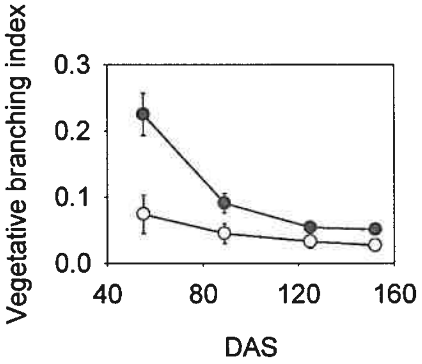

Figure 2. This graph shows the increase in the number of vegetative branches resulting from manually imposed tip and fruit damage across the 1998-99 season. The vegetative branching index represents the number of branches per 0.5 m row of cotton standardised to plant height. The variety planted in this trial was Sicala V2i with 60 kg N / ha applied and at 10 plants per metre.

Relative to tip damage, early season defoliation appears to have a greater impact on the subsequent growth of the cotton plant. In a series of field trials conducted by CRC Industry Development Officers in 1999, tip damage showed little influence on (or even a slight boost to) yield while 100% defoliation of true leaves had a larger negative effect (Fig. 3). These results highlight the difference between depriving a plant of its current growing tip and of its carbon source. The former involves little tissue mass and can be readily replaced by dormant buds while the latter requires major re-establishment of canopy by a carbon-impoverished plant. Such drastic loss of leaves is clearly undesirable but rare (such as a result of hail). Other studies found no yield effect with as much as 80% of leaf area removed (Wilson and Sadras 1998). This shows that when plants are young, they have sufficient time to recover fully from only a small amount of leaf area left. Another issue Fig. 3 raises is the effect of climate on compensation. Because of a lower mean temperature and a shorter season, cotton grown in cooler regions have a reduced ability to compensate and a greater risk of delays in maturity from both tip and leaf damage. Therefore, a full account of the safety margin for full recovery for various cropping regions is essential and is key part of the continuing compensation research.

Cotton response to fruit removal

Damage to cotton fruit is a great concern to growers since it is generally perceived as having a direct impact on final yield. This perception, however, is not always true. In the extreme case, cotton can lose all its fruit without yield loss if the loss occurred early (Sadras, 1996b). In a realistic situation, pests cause damage to a portion of the fruit on the plant and if there is sufficient fruit remaining to replace the lost fruit, there may

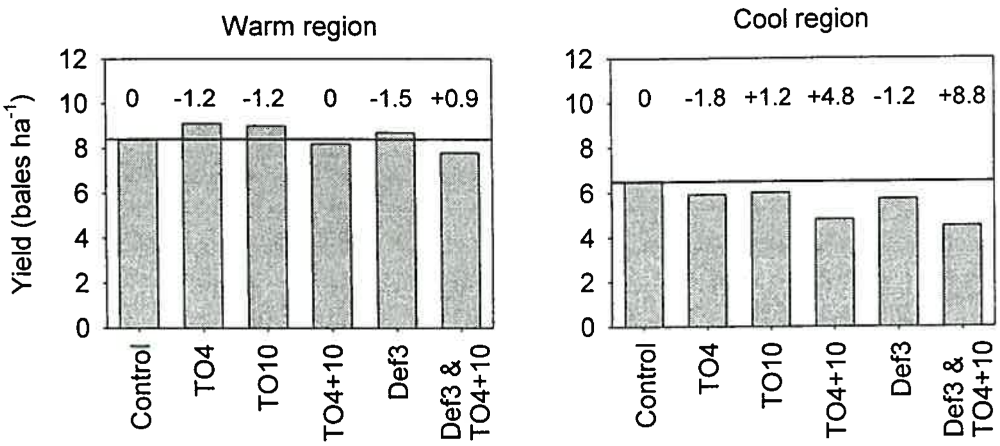

Figure 3. Yield and maturity (numbers above bars) of various tip damage and defoliation treatments conducted in warm (central Queensland) and cool (upper Namoi) cotton cropping regions by CRC Industry Development Officers. Early or delay (in days) in maturity to the control was indicated by – and + numbers respectively. Treatment codes: Control – (no damage), TO4, TO10 and TO4+10 – tipped out at main stem node 4, 10 and both, respectively, Def3 – 100% defoliation (excpet for cotyledons) at node 3.

not be a yield consequence. Taking an average crop as an example, within a metre row, 300 squares may be initiated. However, the crop will lose 2/3 of them through physiological shedding, and will mature typically 120 bolls/m at the end of the season. Physiological shedding occurs because cotton produces more squares than its carbon supply can support. But if a portion of squares was shed through pest damage, then a similar number of remaining squares will be retained to maintain a balance in carbon supply to fruit. Therefore, so long as there are sufficient fruit left on the plant to substitute for that lost to pests and to maintain a fruit load at the plant's carrying capacity (e.g., 120 fruit per metre), then no significant yield loss should occur. How many damaged fruit can cotton substitute? Table 1 gives some idea of the number. This table is derived from the larval feeding model developed by Wilson and Gutierrez (1980) and tested in Australia by Wilson and Waite (1982). Given the developmental stage of the crop (i.e., early squaring with only squares and flowers), we can estimate the number of fruit taken by a cohort of *Helicoverpa* larvae over a 2-week period (from first instar to pupation). Clearly, a healthy crop has enough fruit to substitute for losses caused by 6 or 8 larvae per meter more than once. However, as boll development progresses, there will be fewer squares and more feeding on bolls (lower part of Table 1). Replacing damaged bolls is more energetically demanding than replacing squares. Because there is less time for recovery as the season progresses, boll damage could result in no loss of yield but a significant delay in maturity, or in a yield loss if the damage occurred very late in the season. The limit to compensation late in the season means it is prudent to protect the boll load against damage starting about peak flowering until cut out. Thereafter, without small squares and young terminals on the plants after cut out, first instar *Helicoverpa* larvae will not survive to the next stage. In addition, the combined effect of less attractive maturing bolls (Table 1 – compare LB with other fruit classes when all fruit classes are present) and feeding on young but economically inconsequential bolls means control will not be necessary, particularly after about 15% of bolls have opened (Gibb 1999).

Associated with compensation, first position boll retention is an issue of concern for growers. Currently, a first position fruit retention rate of 50-60% is considered ideal while excessively high rates (above 80%) could incur a yield penalty (ENTOpak, Cotton CRC). With fruit damage, our concern is whether a lower level of retention relates directly to a decrease in yield? This appears not to be the case in the example given in Figure 4. This graph shows no direct relationship between first position boll retention and yield for both transgenic and conventional cotton trialed in the Upper Namoi in 1999. Another key point in this graph is that the two low yielding trials (open circles) were unsprayed but they have retention rates similar to the sprayed trials suggesting that more sprays do not necessarily increase fruit retention. While retention of fruit is important to good yield in general, this can be achieved through larger and more second position bolls. This is one form of compensation where yield is maintained through the substitution of higher position fruit. In cropping areas such as Kununurra WA where the season warms up as fruiting progressed, late forming bolls make up a large portion of the yield (Kay 1998, S. Yeates personal communication). In this situation, the loss of first position bolls lower in the stem will have even less effect on yield.

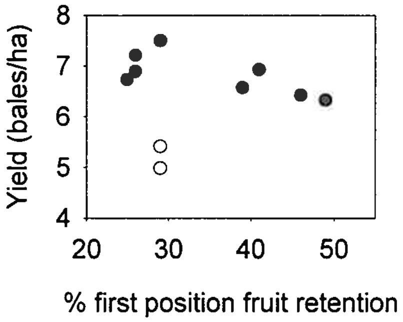

Figure 4. Relationship between fruit retention and yield taken from field trial results conducted by Industry Development Officers in the upper Namoi Valley in 1999. These trials included conventional and INGARD cotton managed under various pest control regimes.

How to harness the compensation potential of cotton?

To be successful in achieving compensation, it is critical to maintain a safety margin between potential pest damage and the crop's ability to tolerate and recover at any given time during the season. Because agronomic and environmental factors vary with time of the season and location, spray decisions should not always be based on static pest thresholds but on the risk of yield loss given the status of the crop and likely weather ahead. The concept of a sliding scale of pest threshold depending on canopy development and fruiting dynamics has been proposed by Hearn and Room (1979) and Wilson (1986). Because we are not yet able to forecast the yield impact at different pest levels and crop conditions, a truly dynamic threshold for pest management has not been widely implemented. Achieving good compensation involves a multitude of interacting factors, the following are a few key points warrant consideration.

Any factor involved in regulating cotton growth may influence how cotton recovers from pest damage. Conditions favourable for rank growth (e.g., irrigated cotton under high soil N) may exacerbate the response to pest damage such as excessive leaf production following tip damage. To reduce the risk of under compensation due to excessive growth, appropriately managing N and irrigation and choosing the right cultivar will help. Okra leaf cultivars with their higher light penetration and better resistance to mites and *Helicoverpa*, may both incur less damage and suffer less impact from responses to pest damage resulting in excessive leaf production.

Good accounting of the time required to recover lost fruit is essential. If fruit damage exceeds the level where substitution can occur (cf. Table 1), then the plant will initiate more fruit development. This could lead initially to a resumption of vegetative growth which may improve the radiation use efficiency (Sadras, 1996a) and a faster recovery of the crop but it could also delay fruit development resulting in a late crop. Therefore it is important to monitor damage during the early fruiting stage to ensure it does not exceed the level of sufficient substitution. For *Helicoverpa*, one way to do this is by comparing the potential fruit damage of larval number per meter (using Table 1) with actual fruit count. The current fruit retention guidelines given in ENTOpak and the Australian Cotton Industry Best Management Practices Manual (Integrated Pest Management section) should also be consulted. In the future, we will make available a decision support system for the assessment of compensation potential (see Future work below).

There is strong evidence suggesting that most cotton crops can tolerate or even benefit from some tip damage as this can lead to an improvement in canopy structure and resource utilisation. However, there is a risk that high input crops may respond to tip damage by excessive leaf growth. This could increase self-shading and respiratory cost, reduce carbon gain, spray penetration and boll number through boll rot. Therefore, maximising compensation must include measures (e.g., cultivar selection, planting density or growth regulator application) to minimise excessive growth.

Encourage the establishment of beneficial insects to reduce secondary pests such as mites and aphids. Crops with fewer sprays or sprayed with softer chemicals could maintain healthier predator populations and inherit fewer problems with secondary pests later in the season. Other options to increase beneficial insects such as adding refuge crops and food supplements such as Envirofeast should also be considered (e.g., Mensah, 1997).

The use transgenic cultivars will significantly alter future pest management strategies. The current one-gene cultivars offer an enhanced early season protection against lepidopteran pests but the efficacy declines with the start of fruiting. Notwithstanding the potential increase in non-Lepidopteran pests (e.g., mirids), the early season *Helicoverpa* protection alone should be used to its full advantage through the promotion of predator / parasitoid populations. Mid- to late season fruit protection of current INGARD cultivars should follow that proposed for conventional cotton.

Future work

The implementation of compensation potential in decision making on pest control is the next major step in our research. To do so, we must make good predictions on the safety margin between crop tolerance and potential pest damage at any stage of the crop development. This involves a large number of variables (e.g., weather, cultivar, fruiting dynamic, damage history) which can only be processed with a computer simulation model. Based on a substantial amount of existing information, we have begun to describe the processes involved in compensation in a cotton growth model (OZCOT, Hearn, 1994). We are currently incorporating into this model response parameters of cotton to vegetative and fruit damage by *Helicoverpa*, mites and other major pests. The value of such a model lies not only in making spray decisions based on its projected yield for a given pest damage event through simulation, but also in finding the best agronomic options such as cultivar, N application, and planting density prior to planting to maximise compensation.

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Table 1. This is a look-up table of the number of fruit that will be damaged when fed upon by a given number of *Helicoverpa* larvae. The number of damaged fruit varies according to the developmental stage and the availability of fruit types on the plant. It can be used to assess the ability of a crop to replace lost fruit given the number of fruit currently on the plants. This table was generated using the *Heliothis* feeding model developed by Wilson and Gutierrez (1980) and Wilson and Waite (1982). Fruiting classes are: SS=small squares <0.5 cm, MS=medium squares 0.5 – 1 cm, LS=large squares >1 cm, FL=flowers, SB=small bolls <2.5 cm, MB= maturing bolls >2.5 cm but with soft boll wall, and LB=late bolls >2.5 cm with hard boll walls.

Fruit development	larvae per metre	SS	MS	LS	FL	SB	MB	LB	Total
Only small to large squares									
	0.5	0.1	1.0	2.5	0.0	0.0	0.0	0.0	3.7
	1	0.3	2.0	5.1	0.0	0.0	0.0	0.0	7.4
	2	0.5	4.1	10.1	0.0	0.0	0.0	0.0	14.8
	4	1.1	8.1	20.3	0.0	0.0	0.0	0.0	29.5
	6	1.6	12.2	30.4	0.0	0.0	0.0	0.0	44.3
	8	2.2	16.3	40.6	0.0	0.0	0.0	0.0	59.1
Squares and flowers									
	0.5	0.1	0.7	1.1	1.3	0.0	0.0	0.0	3.2
	1	0.3	1.4	2.1	2.6	0.0	0.0	0.0	6.4
	2	0.5	2.8	4.3	5.2	0.0	0.0	0.0	12.9
	4	1.1	5.7	8.6	10.4	0.0	0.0	0.0	25.7
	6	1.6	8.5	12.8	15.7	0.0	0.0	0.0	38.6
	8	2.1	11.4	17.1	20.9	0.0	0.0	0.0	51.5
Squares, flowers and small bolls									
	0.5	0.1	0.7	0.9	1.0	0.6	0.0	0.0	3.3
	1	0.3	1.4	1.8	2.0	1.2	0.0	0.0	6.6
	2	0.5	2.7	3.5	3.9	2.4	0.0	0.0	13.1
	4	1.0	5.4	7.0	7.9	4.9	0.0	0.0	26.2
	6	1.6	8.1	10.5	11.8	7.3	0.0	0.0	39.3
	8	2.1	10.8	14.0	15.7	9.7	0.0	0.0	52.4
All except hard bolls									
	0.5	0.1	0.7	0.7	0.7	0.4	0.2	0.0	2.9
	1	0.3	1.3	1.5	1.5	0.8	0.5	0.0	5.9
	2	0.5	2.6	2.9	2.9	1.7	1.0	0.0	11.7
	4	1.0	5.3	5.9	5.9	3.4	1.9	0.0	23.4
	6	1.6	7.9	8.8	8.8	5.1	2.9	0.0	35.1
	8	2.1	10.6	11.8	11.7	6.7	3.9	0.0	46.9
All fruit classes present									
	0.5	0.1	0.7	0.7	0.7	0.4	0.2	0.0	2.8
	1	0.3	1.3	1.4	1.4	0.8	0.4	0.1	5.6
	2	0.5	2.6	2.8	2.7	1.5	0.8	0.2	11.2
	4	1.0	5.3	5.6	5.4	3.0	1.7	0.4	22.4
	6	1.6	7.9	8.5	8.1	4.5	2.5	0.5	33.7
	8	2.1	10.6	11.3	10.8	6.0	3.4	0.7	44.9