Biotechnology for Changing Practice

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Australia's cotton industry has been one of the global success stories in the application and stewardship of transgenic biotechnology to deliver productivity and sustainability gains.

Prompted to adopt new pest management approaches in part to answer social licence challenges – which began in the 1980s and lingered over the following decades – the industry rapidly adopted transgenic insecticidal (Bt) cotton varieties in the 1990s, followed by transgenic herbicide tolerant cotton varieties in the 2000s.

Growers and industry collaborate with biotechnology providers and researchers to improve the technology iteratively. Crucially, all parties worked together to create, enforce and maintain the all-important accompanying resistance management plans required to ensure the biotechnology's effectiveness was maintained as part of an integrated pest management strategy.

This article outlines the development of the various biotechnologies in use in the Australian cotton industry from the 1990s through to the present day, the accompanying resistance management plans (RMPs), and the positive outcomes it has produced for growers, industry, the environment and the community.

Embracing Iterations of GM Cotton

The modern cotton industry heavily relies on genetically modified (GM) technologies, currently with over 99% of total planted area incorporating transgenic traits for insecticidal (Bt) proteins and/or herbicide tolerance. Several iterations of GM traits have been adopted by cotton growers since the introduction of the first genetically modified cotton in the 1996–97 season (Figure 1, over page).

The initial success of the GM cotton varieties was enabled by close partnerships between industry, research organisations, the trait provider and the commercial seed increase company. These partnerships ensured that the traits were incorporated into elite germplasm and delivered to cotton growers with a robust resistance management plan (RMP), a complementary entomologic package and a comprehensive agronomic package, which were all tailored to the Australian cotton production systems.

The industry continues to rapidly adopt new iterations of Bt and herbicide tolerance cotton traits (Figure 1, over page). The introduction of Bollgard® 3 for the 2016–17 cotton season marked a major milestone for innovation in cotton, protecting the longevity of the Bt technology and bringing new benefits to growers. A 92% uptake for the Bollgard® 3 technology for the first commercial growing season (Figure 1, over page) represents the fastest transition to new GM technology anywhere in the world.

Enabling Integrated Pest Management

The introduction of GM cotton provided a platform for augmenting holistic pest management in the Australian cotton industry. The recent and significant impacts of resistance to broad-spectrum insecticides meant that the cotton industry had systems in place, and a strong culture of engaging in resistance management when transgenic cotton was introduced.

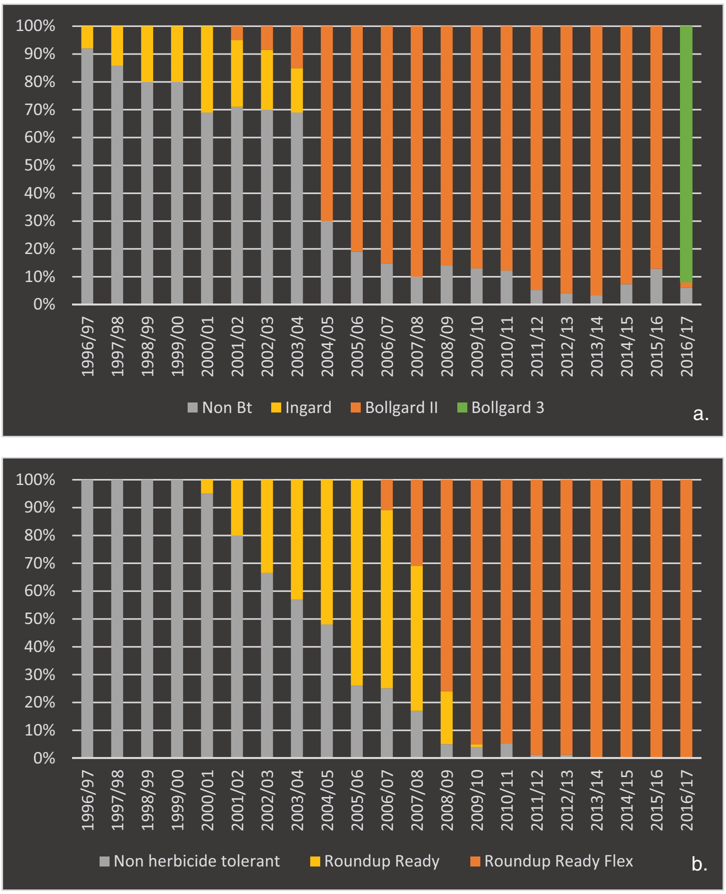

Figure 1: Proportion (%) of total cotton area that was planted to varieties containing (a) transgenic insecticidal (bt) or (b) herbicide tolerant traits since the first commercial GM cotton release in the 1996–97 cotton season, where data for the Liberty Link® (glufosinate tolerance) cotton trait are not presented on account of representing less than 1.2% of total planted area since commercial release in the 2006–07 season.

Source: Monsanto Australia Ltd (2017, unpublished).

Introduction of these traits was treated as an opportunity to entrench integrated pest management (IPM) and integrated weed management (IWM) into Australian cotton production systems. These systems incorporated adoption of a broad range of biological and cultural farming practices, and delivered significant benefit to growers in addition to positive environmental outcomes.

For Bt cotton, in conjunction with insecticidal traits that were efficacious against *Helicoverpa* spp., the industry moved to develop and introduce voluntary strategies to slow the development resistance (Downes et al. 2017; Wilson et al. 2013) including:

- rotating chemistries in accordance with an insecticide resistance management strategy (IRMS)
- utilising selective control options for *Helicoverpa* spp. to preserve beneficial insect populations
- basing spray decisions on thresholds.

These strategies subsequently removed the strong selection pressure on both the newer and older insecticide groups, thus stabilising resistance levels to these chemistries (Bird 2015).

Glyphosate tolerant cotton has enabled cotton growers to include in-crop weed management options within an IWM strategy. It has resulted

in a reduction in use of residual grass herbicides by 62% and residual broadleaf weed herbicides by 33% (Crop Consultants Australia 2003–16), which had significant environmental benefits. The reduced need for hand chipping weeds in the Roundup Ready® system has delivered human health and safety benefits and land conservation benefits have been delivered by a move toward strategic mechanical cultivation (Doyle 2005; Fragar & Temperley 2008).

Since introduction of the first generation of GM cotton varieties, growers have continued to support industry investment in science and monitoring for resistance management. This has contributed to an overall decrease in insecticide use of 90%, compared with non-GM cotton varieties (Crop Consultants Australia 2003–16).

Prioritising Stewardship

Stewardship for transgenic technologies remains a primary priority for the Australian cotton industry to ensure trait longevity. Prior to the introduction of the first commercial Bt cotton in 1995, the Australian cotton industry was aware and actively working to manage resistance risks associated with *Helicoverpa armigera*.

Concerns over season-long expression of Bt proteins in transgenic insecticidal plants led the industry and the technology providers to believe that the ongoing success of Bt cotton in Australia would be dependent on an effective and well-supported resistance management strategy that was based on the best available science, and practical to implement.

Representatives of the Australian cotton industry and scientific community worked closely with trait and product providers to implement scientific programs that determined how the management of resistance risks might be best achieved in practice. The result was a suite of resistance management plans (RMPs) which delivered a science-based and practical approach for managing resistance issues associated with GM cotton traits.

The RMP for Bt cotton is based on in-season dilution of resistance alleles, and quarantine of resistance alleles across cotton seasons. This is achieved by:

- restricting planting and harvesting windows to a defined period to minimise exposure
- planting refuge crops to dilute resistance alleles
- planting trap crops or pupae busting to minimise carry over of resistance alleles between seasons
- limiting Bt exposure by controlling volunteer and ratoon cotton
- spray limitations for topical Bt products.

To date, with a range of resistance management strategies in place, there has been no widespread resistance to the insect pest solutions offered by transgenic technologies for Australian cotton (Tabashnik et al. 2013).

Ongoing evaluation of the efficacy of the RMP is a collaborative effort involving a range of industry organisation, research providers, and trait providers or product registrants. The industry continues to identify research opportunities to improve the RMP, and extension opportunities to ensure compliance. The industry is also working with trait providers, product registrants and regulators to implement industry-led stewardship frameworks to enable industry to respond to emerging resistance issues with greater flexibility, without compromising the longevity of transgenic technologies.

In addition to identification of research opportunities to refine the current RMP, the Australian cotton industry continues to invest in pre-emptive research for future resistance risks. For example, although the underlying mechanism of resistance for Australian *Helicoverpa* spp. to Bt cotton traits is recessive, proactive screening strategies are being implemented to ensure that the industry can detect and respond to future threats associated with dominant resistance mechanisms (Downes et al. 2016).

Collaborative initiatives are being undertaken to better understand field-evolved resistance for insect species in international Bt cotton and Bt corn production system. This information sharing is reciprocated so that the Australian experience can be used to promote IPM and resistance management in international cotton production systems.

Biotechnology for Industry Growth

GM solutions for the cotton industry have driven on-farm practice change with direct environmental and social benefits that have translated to market opportunities for premium products down the value chain.

Bt and herbicide tolerance technologies have delivered a suite of direct and indirect benefits to the industry. Primarily associated with reduced pesticide use, these benefits include reduced input costs and farming risk; improved crop management effectiveness, yield and profitability; and improved environmental and human safety.

A 2016 economic study (Gorddard, R, unpublished) indicated that the Bt cotton resistance management plan has created value for the cotton industry through:

- maintaining a high rate of innovation and productivity growth
- fostering cooperation within the industry
- maintaining a capacity for risk management.

Creating Value on the Farm

Biotechnology has delivered significant gains in integrated pest and weed management that have returned social and economic benefits to Australia cotton farmers, in addition to environmental benefits to cotton growing communities.

Improved decision-making for pest management

Transgenic solutions for insect and weed management have delivered significant benefits to the Australia cotton industry. When growing genetically modified organism (GMO) varieties, cotton farmers now use at least 90% less insecticides, 62% less residual grass herbicides and 33% less residual broadleaf weed herbicides (Crop Consultants Australia 2003–16).

Widespread adoption of the three iterations of Bt cotton has reduced the number of on-farm insecticide spray applications to one to three per season, with some crops no longer being sprayed at all. This equates to a reduced environmental impact quotient of 64% for Bollgard® II cotton compared with non-GM cotton in Australia, even when the Cry proteins are included in the assessment (Knox et al. 2006).

Reductions in total pesticide use have resulted in indirect impacts for the decision-making ability of cotton growers around pest management strategies. This shifting focus for chemical application to IPM systems has allowed growers to make better decisions around pest management including ranking insecticides based on harm to natural enemies; applying food sprays on crops to attract natural enemies; establishing decision-making rules of thumb such as ratios of natural enemies to pests; and identifying resources that can support natural enemies (Downes et al. 2017).

Environmental benefits have also been derived from cotton growers being able to adopt a more holistic approach to best practice management across the farm, instead of pest management driving decision-making (Gorddard, R, unpublished). This has driven gains in resource-use efficiencies, including a 40% increase in water use efficiency (Figure 2, over page). For cotton farms and cotton catchments, indirect environmental benefits of GM include; improved populations of beneficial insects and wildlife in cotton fields; reduced pesticide run-off, air pollution and waste from the use of insecticides; lowered carbon footprint and fossil fuel use; improved soil quality; and improved land use efficiency (ICAC 2000; Brookes & Barfoot 2012).

Cost savings

Unlike many countries using Bt and herbicide tolerant biotechnologies, Australian cotton growers have rarely derived yield gains from using transgenic traits in cotton. This largely reflects the effective use of pesticides for insect and weed control prior to introduction of these technologies, with the primary advantage being derived from lower costs of production (Brookes & Barfoot 2012).

The direct cost savings from the introduction of Bollgard® II cotton (after taking into consideration the cost of the technology) had delivered significant net gains of up to \$241 ha^{-1} by 2010, associated with lower insecticide costs. At a national level, this translated to approximately \$114.2 million net farm income gain which was equivalent to an annual increase in production of 41.6% (335,720 tonnes). For Roundup Ready cotton, net gains of \$36 ha^{-1} were estimated by 2010, translating to approximately \$18.6 million total farm income (Brookes & Barfoot 2012).

For Roundup Ready Flex cotton systems, cost savings are also associated with simplified logistics; occupational health and safety concerns; ability to grow a productive crop in heavily infested fields; and improved seedling vigour and competitiveness associated with avoiding impacts caused by residual herbicides (Doyle 2005).

Healthier workers

The introduction of transgenic insecticidal and herbicide tolerant cotton crops is associated with a range of positive changes for the health and safety of cotton growers, farm workers and chemical contractors (Fragar & Temperley 2008).

Overall, most Australian cotton farmers find GM cotton to be more profitable and easier to grow than conventional cotton. This has improved flexibility, certainty, and risk management associated with farming operations for GMO cotton systems. Improved work-life balance associated with reduced commitments for less labour-intensive cropping systems have also been reported for transgenic cotton crops (Doyle 2005).

Changing pesticide use patterns associated with transgenic cotton crops have also delivered reported health benefits. Transgenic cotton crops are associated with decreased occupational health and safety (Fragar & Temperley 2008) incidents:

- reduced in-field activity including vehicle movement, chipping operations, marking for aerial pesticide applications, ground pesticide sprays, and tillage
- reduced injuries associated with aerial spraying operations
- reduced injury caused by manual weeding including sunburn, rashes, cuts and abrasions
- reduced pesticide exposure during mixing and application
- reduced exposure to fuel, insect, solar radiation, crop, and trip hazards associated with reduced field work
- reduced stress associated with night work, spray failures and insecticide resistance.

Creating Value Beyond the Farm Gate

Healthier communities

Benefits associated with worker safety have translated to a community level whereby reduced pesticide applications have improved neighbour safety through reductions in air pollution and improved water quality (ICAC 2000).

Improvements in environmental and human safety have delivered social value for the cotton industry, through improved perceptions in over 150 cotton communities. A survey of community perceptions to the cotton industry showed decreasing concerns regarding pesticide use remain in cotton growing districts, which may be associated with the update of Bt cotton technologies and implementation of the industry's best management (*my*BMP) program (Pyke & Doyle 2006).

The negative media attention and resulting community outrage around issues with the overuse of pesticides by the Australian cotton industry in the mid-1990s and early 2000s have largely disappeared as the industry has transformed its practices on-farm. Cotton farmers are now viewed as valued and positive contributors to cotton communities, sustainable primary producers, and of huge economic importance to those regions where cotton is grown.

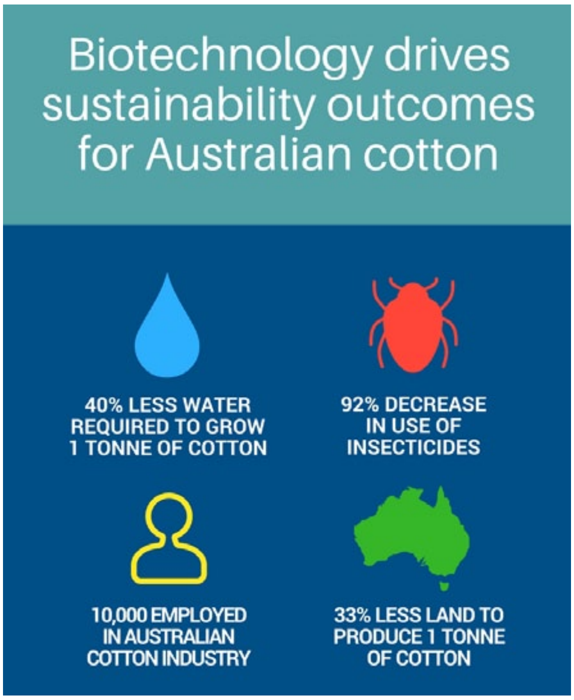

Figure 2: Snapshot of sustainability outcomes indirectly enabled by GM cotton, where growers can focus on holistic approaches to best management practice, rather than only pest control.

Source: Adapted from the Australian cotton grown sustainability report (Roth 2014).

Sustainability outcomes for market access

Transgenic solutions for insecticide and herbicide tolerance traits have enabled the industry to deliver short- and long-term sustainability outcomes (Figure 2) for reduced pesticide use and improved environmental and human safety (Fragar & Temperley 2008; Doyle 2005; Brookes & Barfoot 2012; ICAC 2000; Knox et al. 2006). These changes have been documented through the industry's 21-year history of independent environmental assessments and are highlighted in the most recent Australian grown cotton sustainability report (Roth 2014).

Improvements in the sustainability credentials of the Australian cotton industry have not only delivered direct benefits for farmers, farm workers, the natural environment and cotton communities, but have also created value down the cotton supply chain as brands, consumers, and governments around the world are increasingly interested in the sustainability of agriculture and raw materials.

Improved sustainability credentials have enabled participation in global cotton identity programs such as the Better Cotton Initiative (BCI) and the Cotton LEADS Program. With many more major brands and retailers setting bold targets for sourcing sustainable cotton, alignment of the Australian best management practice standards with international sustainability frameworks is key to ensuring ongoing market access for Australian producers.

A key part of the positive story is the successful uptake and management of GM cotton varieties that require significantly less pesticides. However, GM cotton (non-organic) is still seen by many leading global brands and NGOs as a problem in some cotton production systems around the world. Australia's environmental success story with biotechnology is an important part of the message to groups making decisions about how to define 'sustainable' cotton in sourcing portfolios.

In conjunction with advanced decision-making frameworks and crop management tools, the delivery of new traits using gene technologies are expected to further drive sustainability outcomes for Australian cotton, particularly for improved resource-use efficiency. The delivery of these and other cutting-edge innovations will remain a centrepiece of the Australian cotton story, told throughout the supply chain to ensure Australian cotton remains a fibre of choice for Australian and international brands and manufacturers.

The Future for Cotton Biotechnology

A regulatory environment that fosters innovation

Biotechnology will continue to play a major role in improving the productivity, quality, and sustainability of cotton produced in Australia. Importantly new breeding techniques could be applied to overcome significant technical challenges in plant breeding for polyploid plants, including cotton. However, whether these advancements are made using traditional GM approaches, or alternative gene technologies that do not technically result in GMOs, will depend on the regulatory environment and subsequent registration/licensing costs, as well as the outputs that these technical solutions can deliver.

Application of rapid innovation in synthetic biology to cotton production systems would be accelerated by modernisation of the regulatory framework for products derived from gene technologies.

There now exists a continuum of techniques between those traditionally considered to mimic natural processes and those which result in a genetically modified organism. Additionally, new techniques that can deliver significant advances with a risk profile that is commensurate with natural processes, should be regulated accordingly.

In order for innovation to be fostered in this space, the underlying regulatory framework needs to be sufficiently flexible to accommodate these advances in gene technology, whether they relate to plant incorporated, or topically applied technologies.

A modern regulatory framework for gene technologies should deliver a robust system for science-based and risk-aligned regulation that protects human health and the environment as part of a clear and predictable path to market. It should also provide certainty for consumers, where community perceptions towards the use of synthetic biology for agricultural advancement may result in market implications for the cotton industry's ability to adopt technologies resulting from new breeding techniques.

A review of the current regulatory system and related legislation is essential to ensure that Australia's scientists and cotton growers are best positioned to utilise technological advances that deliver on sustainability outcomes for the Australian cotton industry.

The Next Generation of GMOs

Stacking of insecticidal and herbicide tolerance traits is likely to continue to increase longevity of current technologies, which will require continual refinement of the accompanying stewardship packages to address emerging resistance issues. However, the efficacy and longevity of future GM traits may be enhanced by coupling with new approaches in synthetic biology. For example, stacked traits for pest management could be accompanied using gene drive to increase susceptibility of insect populations to chemical products, and partnered with topical or incorporated protectants – eg RNAi (ribonucleic acid interference) – to develop robust IPM and IWM approaches.

Biotechnological solutions currently being investigated as part of broader research effort may have implications for addressing a range of biotic and abiotic constraints to cotton production in Australia including:

- tolerance or resistance to a suite of endemic and exotic insects and plant pathogens
- tolerance or resistance to abiotic stresses including drought or heat stress
- nutrient use efficiencies, particularly for nitrogen
- novel fibre properties
- altered cell wall composition or modified seed oil compositions
- accelerated growth and development including translational photosynthesis.

In addition to addressing yield-limiting constraints to cotton production, these solutions may deliver long-term sustainability outcomes or change the direction of the industry's supply chain. For example, novel fibres with altered cell wall composition could create new uses for fibre in textiles manufacturing, such as nanocomposites.

Regardless of whether genetic advances for the cotton industry are delivered by GM or non-GM technologies, varietal advancement for cotton will continue to require; delivery through a strong conventional breeding program for elite germplasm; strong agronomic packages to ensure that rate-limiting factors are all addressed; accessible decision-support tools for sustainable production systems; and industry-level stewardship programs to ensure longevity of the technology.

Ongoing Pest Management Challenges

Despite substantial efficacy and efficiency gains for pest management in transgenic cotton crops, challenges still exist within the industry's IPM and IWM systems.

While the major pest, *Helicoverpa* spp. are controlled by Bt cotton, sucking pests such as mirids (*Creontiades dilutus*) and aphids (*Aphis* spp.) that were incidentally controlled by broad spectrum chemistries in conventional cotton systems have emerged as issues for cotton (Wilson et al. 2013). Introductions of exotic silverleaf whitefly (*Bemisia tabaci* Biotype B) and mealybugs (*Phenacoccus solenopsis*) have further increased these challenges.

While weed control has largely improved under herbicide tolerant cotton systems, the increased reliance on glyphosate has seen a species shift towards weeds that are resistant, tolerant or difficult to control in glyphosate systems including ryegrass (*Lolium rigidum*), fleabane (*Conyza* spp.), and Feathertop Rhodes grass (*Chloris virgata*). These challenges have been exacerbated by a loss in capacity for integrated weed management in cotton, including equipment and skills for use of alternative weed management tactics.

To preserve the efficacy of GM cotton traits and address these arising issues, the industry collectively is striving to move towards integrated insect and weed management systems that are coordinated across crop types, landscapes and seasons.

Conclusion

The adoption of biotechnology by the Australian cotton industry is a fine example of growers and industry working hand-in-hand with technology providers and researchers to produce outcomes that are not only beneficial to cotton crops, but also for the environment and the community.

The Australian cotton industry continues to provide leadership for stewardship of GM products within integrated pest management systems, particularly around resistance management for cotton insecticidal and herbicide tolerant traits.

The collaborative efforts of Australian cotton growers, researchers, industry leaders and technology providers to drive adoption of new technologies, and associated best practice principals for integrated pest management systems are attributable to improvements in the productivity and profitability of Australian crops. This has resulted in a thriving cotton industry that is renowned for high yielding and quality products, and now an enviable environmental and social record.

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About the Author

Dr Nicola Cottee is a Policy Officer (Research Direction and Stewardship) with Cotton Australia who works to protect Australian cotton crops from endemic and exotic pests, and to ensure that cotton growers have a voice for industry research and development investment.

Nicola strongly advocates for grower-guided investment in research and extension to underpin best practice principles for the Australian cotton industry. Her work with Cotton Australia assists delivery of long-term sustainability outcomes to ensure Australian cotton remains a fibre of choice for international brands and manufacturers.

In a longstanding association with cotton research, Nicola's previous role with CSIRO involved implementation of a multidisciplinary research program to improve the resilience of cotton crops to high temperature stress.

Nicola holds a Bachelor of Science in Agriculture (Honours) and a PhD from the University of Sydney.