



Insecticide Management in Cotton: Progress and Prospects

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Abstract

Chemical insecticides continue to be a necessary input for profitable cotton production. Recently, cotton's share of the global insecticide market declined from 24% in 1994 to 14.8% in 2010. Such a decline did correspond with the increased adoption of transgenic cotton during that period. Prior to the introduction of *Bt* cotton in 1996, bollworms had accounted for at least 50% of all chemical insecticides used on the crop annually. *Bt* cotton is toxic to bollworms and generally does not warrant any supplemental need for insecticide use, except when bollworms develop resistance to *Bt* cotton. Estimates show that extensive cultivation of *Bt* cotton resulted in the reduction of insecticide usage by 268.6 million kilograms (kg) from 1996 to 2015 (Brookes and Barfoot, 2017). However, the recent increasing trends in the use of insecticides have been necessitated by the need to suppress a global resurgence of sucking pests, as well as the pink bollworm, which has recently developed resistance to *Bt* cotton in China, India and Pakistan. On conventional cotton, the rise in insecticide use has been in response to the growing need to deal with the increased spread of some major cotton pests across continents, and the advent of insecticide resistance. In low-income countries, increased use of insecticides is also being fuelled by increased informal trade in pesticides due to rampant market failures. In this paper, I discuss these developments together with some of the steps that are needed for more sustainable insecticide use in cotton.

Key words: cotton, insecticides, IPM, externalities, sustainability, market failures

Introduction

Cotton is the world's most important natural fibre. It is grown on up to 3% of the world's arable land in many countries located between 37 and 32 degrees north and south of the equator respectively (ITC, 2011). Cotton is thus one of the few crops of major economic importance worldwide that is produced in both developed and developing economies. In the latter, cotton is often regarded as the answer to poverty alleviation and export-income generation. To date, up to 80% of cotton's annual global output is produced by smallholder farmers living in Asia, China and sub-Saharan Africa (SSA). The remainder is produced by large farmers in developed countries (Kranthi, 2018).

On the global fibre market, cotton's share in textile production has dropped from 68% in 1960 to just 26.5% in 2018 (ICAC, 2019). Due to rising cost of production, cotton has been losing its market share to synthetic fibres, whose share currently stands at 66.1%. The major driver for cotton's rising production cost has been the worldwide upsurge in the use of agrochemicals, mainly insecticides. In 2006, crop protection accounted for up to 45% of variable costs in cotton production in low-income countries (Russell and Kranthi, 2006). Due to emerging pest problems, the use of insecticides worldwide has risen, resulting in cotton's market share climbing from 14.8% to 16.1% between 2010 and 2014 (Ferrigno *et al.*, 2017; Kranthi, 2018). Paradoxically, this is happening at a time when average yields in low-income countries are still well below the global average yield of 772 kg lint/ha (Kranthi, 2018).

Because the bulk of cotton is grown in tropical and sub-tropical areas — where pest pressure tends to be severe — greater use of insecticides in such countries is perhaps a reflection of that fact. However, the use of insecticides in low-income countries often tends to be inappropriate and not based on rational and carefully considered criteria (Russell and Kranthi, 2006). George Santayana had earlier warned through his prophecy that 'those who cannot remember the past are doomed to repeat it'. In light of what happened on cotton last century (see Smith, 1969) and its bearing on what is happening now, we may already be heading towards a precipice — unless and until cotton stakeholders urgently revisit their current production and protection strategies. We need to reduce and optimise insecticide use and thus make cotton productive, profitable and sustainable in the long term.

Smallholders Vis-a-Vis Large Farmers

Smallholders are best described as farmers practicing a mix of commercial and subsistence production, in which the family provides the majority of labour and the farm provides the principal source of income (Narayan & Gulati, 2002). They tend to prioritise food-crop production and often allocate land to cotton and other crops on the basis of considerations such as available labour, land, input requirements and selling prices. Furthermore,

because cotton is often sown after food crops, it tends to be not well-looked-after, agronomically. These and other considerations tend to have a strong bearing on the types of yields that smallholders get from their cotton.

In developed economies, farmers often adopt a high-input, high-output approach to cotton production on large plots of land. However, due to increased adoption and use of integrated pest management (IPM) practices and other tools, their overall insecticide use patterns tend to be far more organised than in the case of smallholders in low-income countries. Furthermore, due to strong concerns on resistance, environmental pollution and other health-related issues, the use of insecticides in developed economies often tends to be subject to more stringent legal and regulatory controls (Matteson, 1995) than in low-income countries, where proper regulatory controls are lacking and many governments have failed to support independent research on pesticides.

Insecticide Use Trends in Cotton

There are reportedly 1,326 species of insects and other arthropods associated with cultivated cotton worldwide (Hargreaves, 1948). Many of the insects recorded in a cotton field just happened to be there when collected, but were not pests. Nevertheless, a complex of lepidoptera comprising of *Helicoverpa armigera*, *Helicoverpa zea*, *Helicoverpa punctigera*, *Heliothis virescens*, *Earias* spp, *Diparopsis* spp and *Pectinophora gossypiella* are frequently the most damaging to cotton. They tend to be collectively referred to as bollworms because their larvae have a propensity to preferentially feed on cotton's bolls as well as other fruiting points, thus affecting yield directly. For prevention of such damage, bollworms as a group account for well over 50% of all insecticides used on cotton globally (Fitt, 1989; Shelton *et al.*, 2002). To date, most of the sucking pests that were previously categorized as secondary pests have now assumed full economic status on transgenic cotton and are being targeted for insecticidal control (Ferrigno *et al.*, 2017; Kranthi, 2018). This is currently a big issue because those supporting Bt cotton failed to clearly emphasize that Bt toxins only killed lepidopteran larvae.

Prior to 1960, the bulk of the cotton in SSA was grown without the use of insecticides (Matthews, 2014). The use of cultural practices such as early planting was encouraged in order to allow the crop to mature and be picked before late pests such as *Dysdercus* spp, *Oxycarenus* spp, and others moved onto the crop. Although early-sown cotton is more likely to recover or even escape attack from *H. armigera* than late-sown cotton, farmers' tendency to sow food crops first often tends to make this recommendation unpractical. To circumvent such problem, the use of varieties that flower rapidly over a relatively long period of time and, consequently, being capable of compensatory

flowering in the event of early season bollworm attack was advocated (Reed, 1965). To control *P. gossypiella*, farmers were compelled to destroy crop residues after harvest and to observe a mandatory three-month closed season thereafter. The closed season was mandatory after about 1938 (Matthews, personal communication). In SSA, plant leafhoppers that are commonly referred to as jassids, *Jacobiasca lybica* — which tended to kill the cotton crop during its vegetative stage — have, over time, tended to be controlled by mere selection for increased leaf hairiness in cotton genotypes, a morphological trait which confers resistance to cotton varieties. Although work on this pest began in the early 1920s it remained unpublished until 1949 (Parnell *et al.*, 1949).

Following the advent of chemical insecticides, farmers have tended to prefer them to non-chemical methods and such attitude tends to be promoted by agrochemical companies. There is a conspicuous paucity of data on insecticide use on cotton in most countries. Available information indicates that cotton's share of the global insecticide market declined from 24% in 1994 (Myers & Stolton, 1999) to 19% and 14.8% in 2000 and 2010 respectively (Ferrigno *et al.*, 2017). However, by 2014 cotton's market share had risen to 16.1% (Ferrigno *et al.*, 2017). The decline in insecticide use between 1994 and 2010 corresponds with a period of increased adoption of transgenic cotton and use of IPM practice. The surge in insecticide use from 2014 onwards occurred worldwide on both transgenic and conventional cotton.

Drivers for Increased Insecticide Use on Cotton

H. armigera and white flies have become resistant to chemical insecticides: The case of SSA

In West and Central Africa (WCA), the institutional set up has for many years promoted a high-input cotton production (Tschirley *et al.*, 2009). As a result, farmers there have been getting higher average yields per ha than farmers in Eastern and Southern Africa (ESA). However, statistics from WCA have shown declining cotton yields and increased pesticide use (Zepeda *et al.*, 2007). Because cotton in WCA has tended to be sprayed more frequently than cotton in the ESA (up to 15 times for the former, as opposed to just 6 to 8 times for the latter), *H. armigera* and *Bemisia tabaci* became resistant to pyrethroid insecticides in WCA but not in ECA — despite having been introduced for use on cotton at about the same time in the early 1980s (Kabissa, 1997; Martin *et al.*, 2005). Furthermore, because sucking pests in WCA move into cotton from vegetable crops and vice versa, spraying both host plants with insecticides with the same mode of action inevitably speeds up resistance.

Figure 1. African bollworm, *Helicoverpa armigera* - damage to squares



Figure 2. Spotted bollworm, *Earias vittella* - damage to squares



Technological responses to pest problems do not last forever: The case of *Bt* cotton

It is a truism that where transgenic cotton became commercialised, most bollworms became quickly relegated to non-economic status. In such countries, insecticide spray frequencies as well as overall quantities of insecticides used on cotton declined significantly (Shelton *et al.*, 2002). However, other insects — notably white flies, mirids, stink bugs and mealy bugs, which were previously regarded as secondary pests prior to the introduction of transgenic cotton — have now become *de facto* economic

pests in most countries wherever transgenic cotton is being grown (Ferrigno *et al.*, 2017; Kranthi, 2018). The change in pest status of sucking pests following widescale adoption of transgenic cotton has necessitated the increased use of insecticides in order to control them.

In some countries, most notably India, severe damage by insect pests has continued to occur even on Bt cotton, thus necessitating a resumption of insecticide sprays against it. Such situations are being blamed on weak regulatory and legal controls on systems for the production, multiplication, distribution and sale of Bt seed resulting in rampant parallel markets for the sale of recycled seed as well as cheap but fake Bt seed (Ferrigno *et al.*, 2017; Kranthi, 2018). Due to lack of proper agronomic controls on the release of cotton varieties in India, more than 800 new Bt cotton hybrids were approved during 2006 to 2011, most of which were susceptible to sap-sucking insects, which resulted in doubling of insecticide use on cotton during the period (Kranthi, 2013). Insecticide use increased further after 2011 in India due to the development of insecticide resistance in jassid and whiteflies, and resistance of pink bollworms to Cry1Ac in 2009, and to Cry1Ac+Cry2Ab in 2014. In China and Pakistan, the continued use of varieties containing the single *Cry1Ac* gene has resulted in populations of the pink bollworm, *Pectinophora gossypiella* becoming resistant to Bt toxins, thus compelling farmers in these countries to use insecticides on Bt cotton (Kranthi, 2018). These developments serve to further confirm the fact that technological responses to insect pest problems do not last forever.

Increased globalisation of cotton pests

Cotton has recently witnessed an increased expansion in the range of some well-established pests into new areas across the globe. To minimise crop losses due to such 'new pests', farmers have had to spray their crops more than would normally be the case. Some of the recently introduced pests include the boll weevil *Anthonomus grandis grandis* into several South American countries including Argentina, Brazil, Colombia and Paraguay (Showler, 2009). In Africa, the fall armyworm, *Spodoptera frugiperda* was first spotted in Benin and subsequently reported in Nigeria in 2016. It has now spread to India and 44 countries in SSA where it has been causing extensive damage to several crops, maize in particular (Rwomushana *et al.*, 2018). In 2018, the fall

armyworm caused severe damage to maize and cotton in Tanzania. For cotton, none of the synthetic pyrethroids that are normally used for control of *H. armigera* were able to suppress it. In Brazil, the entry of *H. armigera* after 2012 necessitated an increased use of insecticides on cotton and on its non-transgenic host plants. Entry of the boll weevil has also tended to complicate the use of refugia in insecticide resistance management programs for Bt cotton (Barbosa, 2016). A new mega-pest due to hybridisation of *Helicoverpa armigera* and *Helicoverpa zea* was discovered in Brazil in 2017 (Liete *et al.*, 2017; Anderson *et al.*, 2018). This hybrid pest poses a huge threat to cotton and many other crops in Brazil and rest of South America. Due to the lack of institutional capacities to deal with the spread of invasive pest species, low-income countries will continue to depend to use fire-brigade-type approaches to dealing with new pests.

Market failures in low-income countries

The trend toward increased use of insecticides on cotton in many low-income countries is partly an outcome of market policy reforms that started in the early 1990s. Cotton farmers in SSA were previously dependent on marketing cooperatives, marketing boards or state-owned companies for their supply of seasonal inputs. Colonial and post-independence administrations had opted to use such institutions because they had long realised that for the reasons of geography and poverty, smallholders are the most difficult group for private traders or even the government to reach (Dorward *et al.*, 1998). Furthermore, the presence of relatively few key actors on the cotton market tended to facilitate an easy regulation and control of some relative sensitive inputs, insecticides in particular.

After liberalisation, the proliferation of informal trading resulted in all kinds of insecticides becoming available to farmers, who increasingly made their own decisions on which insecticides to buy and use. This was further helped by insecticide retail prices becoming cheaper as patent protection for most insecticides expired and their sale as generics took effect (Shepard and Farolfi, 1999). In Tanzania for example, the number of pesticide outlets between 1995 and 2001 increased by 30% (Williamson, 2003). More recently, Kabissa (2016) found out that although cotton farmers sourced up to 30% of their insecticide needs from retailers and open markets, 40% of such insecticides had an expired 'use by' date. As a result of informal trading, counterfeit agrochemicals in Kenya accounted for up to 15% of the pesticide market and caused between 40% and 60% yield losses where they were used (Williamson, 2003). Due to weak enforcement of pesticide legislation in low-income countries, informal trade coupled with aggressive marketing of insecticides has resulted in some highly hazardous pesticides continuing to be widely available to predominantly illiterate farming communities. In 2017, the use of monocrotophos and

other highly hazardous insecticides on late cotton in India caused the deaths of 63 farmers in the central Indian state of Maharashtra (Matthews, personal communication).

In many ESA countries, some attempts were made to deal with the seasonal input supply problems in a post-liberalisation era by introducing some form of contract-farming arrangements (Minot & Sawyer, 2014). To date, such attempts have been met with mixed results. The ability and willingness of ginners to provide services such as input credit, extension services and market outlets for farmers' seed cotton has tended to be undermined where the number of ginners operating in the country is quite large, and hence contract farming agreements are becoming plagued by rampant malpractices involving side-selling by farmers on one part, and side-buying by ginners on the other. Such tendencies have quite often proven disruptive to contract sanctity, and no doubt contract-farming arrangements are not as widespread as they were expected to become (Tschirley *et al.*, 2009; Minot & Sawyer, 2014). In WCA — where an alternative model involves the use of semi-privatized cotton companies such as SONAPRA, SOFITEX, SODECOTTON, CMDT and SODEFITEX in the provision of input credit and other key services to cotton farmers — there are indications that it is also susceptible to several malpractices, notably the diversion of insecticides destined for cotton to food crops, as well as their sale across national borders (Ferrigno *et al.*, 2017).

Impacts of Increased Insecticide Use on Cotton

An accepted fact about chemical insecticides is that they do not permanently resolve any of the pest problems facing society. However, what is not apparent to most smallholder farmers is the fact that while chemical insecticides may be relatively cheap to individual users, they tend to impose negative consequences on the larger community of farmers because of their side effects. Insecticides are known to have a cost beyond their purchase price when overused, improperly handled, and poorly applied, resulting in their up-front purchase price being often more than doubled by hidden costs to society in relation to dealing with insecticide-induced resistance, suppression of natural enemies, and environmental pollution (Knippling, 1979; Regev, 1984; Wilson & Tisdell, 2001).

Cotton's production history has tended to be characterised by narratives largely pertaining to the negative impacts associated with the over-exploitation of chemical insecticides. The stories of cotton in the Canete Valley of Peru in the 1960s, Rio Grande Texas in the 1970s, Ord River Valley in Australia in the 1980s, and the Gezira Scheme in Sudan in the 1960s (among many others) vividly confirm that the use of chemical insecticides in cropping systems is analogous to using a double-edged

sword (Wilson & Tisdell, 2001). What happened in Sudan — where the use of insecticides against jassids, Sudan's then key economic pest in the early 1960s, helped to elevate *H. armigera* from a secondary pest to an economic pest — has a strong bearing on what is happening on Bt cotton today. The elevation of *H. armigera* from a minor cotton pest to a major cotton pest after 1981 subsequent to the introduction of synthetic pyrethroids in India is yet another pointer to indicate the double-edged nature of insecticides. The current upsurge in sucking pests on cotton worldwide is a significant testimony of how agroecosystem disruption, by either introduction of new varieties or chemical insecticides *per se* or by *Bt* toxins, can bring about the resurgence of previously innocuous pests on crops.

Apart from resistance and resurgence, indiscriminate use of chemical insecticides has had other impacts relating to the environment in general and human health in particular. In India, users of a knapsack sprayer often hold the nozzle on the lance in front of their bodies, resulting in poor pesticide distribution in the crop — and greater exposure to the operator, causing more deaths when using highly hazardous insecticides (Matthews, personal communication). In spite of the paucity of published data on insecticide-related cases of poisoning, deaths and chronic ailments, it is obvious that low-income countries tend to incur high pesticide-related health costs (Wilson & Tisdell, 2001; Ferrigno *et al.*, 2017).

The Need for Insecticide Management

Insects and their allies will continue to be our principal competitors for a limited food and fibre supply (Winston, 1998). In order to minimise their impacts, we have to adopt insecticide management programs that seek to use insecticides more rationally than in the past. Because the use of chemical insecticides may pose risks to human health, non-target species and to the environment — and because insecticides have a tendency to be freely disseminated into the environment and to become ineffective through over-use — our approach to using them should rigourously take these aspects into consideration ((NAS, 2000).

1st Step: Changing the mindset

Mankind has tended to regard insect pests as a problem to be controlled rather than an integral part of nature that should be managed in effective and environmentally responsible ways (Winston, 1998). This mindset has to change because, for every

action contemplated against them, insects have always found ways of countering or circumventing our actions. The idea that insects, too, have a right to life can perhaps be best illustrated by what happened to the Christian Apostle Paul in Turkey. During one of the nights that he spent on a missionary trip, he realised that the guest house where he was due to spend a night was heavily infested by bedbugs. Rather than calling for divine power to kill them, he merely commanded them to exit the house and to stay outdoors. The next morning, he simply allowed them back in (Cimok, 2012). The need to exercise restraint prior to dealing with insect pests on crops is one of the underlying principles of IPM. The latter clearly and emphatically advocates for tolerance of insect damage up to some threshold level beyond which corrective action is to be taken against them. In other words, IPM calls for our qualified coexistence with arthropods. More importantly, building up and conserving beneficial fauna in the cotton ecosystems by carefully considered human interventions would go a long way toward ensuring sustainable eco-friendly pest management. Such interventions are mainly related to introduction of new varieties, pesticides and cropping practices.

2nd Step: Switching from preventive to 'as-needed' spray programs

Until recently, insecticide use on cotton has tended to be based on the age-old norm of either weekly or bi-weekly sprays of designated insecticides, starting either at the start of flowering or a designated number of days after planting. To date, the need for a paradigm shift from such prophylactic or preventive calendar-based 'rain of death' regimes to 'as-needed' spray programs is being

Figure 3. Monitoring fields for pest damage and economic threshold levels



Figure 4. Training field scouts for insect pest and disease monitoring



necessitated by the fact that insect pests neither occur on cotton regularly, nor do they always cause economic damage when present. However, if the switch is to be successful, farmers need to be trained on how to use practical and research-based action thresholds, based either on pest-infestation or crop-damage levels, and how to correctly identify the pest species in question — as well as the natural enemies that occur on cotton from time to time. Ideally, farmers will base their decisions on whether to spray or not on some combination of these parameters (Matthews, 2014). Further, following proper pesticide-application technologies also strengthens IPM approaches.

Since the early 1970s, farmer in Zimbabwe have been coached on how to rationalise insecticide use on cotton against *H. armigera* and *D. castanea* through the institutionalisation of scouting and threshold spraying using the peg board (Matthews, 2014). Similarly, farmers in Egypt have for ages been using spray windows in order to optimize the control of *P. gossypiella* and *Spodoptera littoralis* by insecticides (Sawicki *et al.*, 1989). In the aftermath of massive pesticide control failures in Burkina Faso, Ivory Coast and Benin in the 1990s, farmers in most WCA countries have increasingly adopted a practise called 'targeted spraying', which requires them to scout their cotton fields for pests on 40 plants on a weekly basis, and to use designated fixed-action thresholds for the main cotton pests — and to spray only if those thresholds are attained. Deployment of such approach was facilitated by adoption of the Farmer Field School approach to train farmers; significant reductions in pesticide applications were achieved (Martin *et al.*, 2005; Settle *et al.*, 2014).

3rd Step: Switch from generality to selectivity

To date, pressure from scientific advances, societal concerns and regulatory demands have necessitated the withdrawal of some well-known but old and hazardous insecticides, has resulted in the development new insecticides with lower impacts on human health and non-target organisms; new modes of action (hence with lower pest-resistance potential), and a high compatibility with on-going IPM programs (NAS, 2000). In short, there has been a gradual shift from the use of 1st generation neuroactive insecticides — which were effective, inexpensive and persistent — to newer, selective and relatively safer products such as avermectins, neonicotinoids and anthranilic diamides, among others. On cotton, the most widely used chemical insecticides belong to just three major insecticide categories; synthetic pyrethroids,

organophosphates and neonicotinoids (Kranthi, 2018). In order to deal with some of cotton's new and emerging pest problems, a shift towards newer chemistry and other tactics, such as the use of seed treatment with systemic insecticides, should be investigated. Such approaches may provide answers to resurgent early-season sucking pests.

4th Step: Promote increased use of multiple tactics (Integrated Pest Management)

In SSA, the use of a combination of crop-management practices and use of designated varieties to deal with specific pests such as jassids allowed for the successful commercialisation of cotton prior to the introduction of chemical insecticides. Even after the introduction of insecticides, their use remains limited largely because most farmers could not afford to use them as frequently as recommended by R&D institutions on sheer cost considerations. Scouting was thus introduced in order to help them economise insecticide use and optimise production costs. However, as their use on cotton has intensified — particularly in WCA — resistance finally appeared. Insecticide resistance is unknown elsewhere in SSA where a low-input/low-output approach to cotton production still holds (Matthews, 2014).

In other cotton-growing countries outside SSA, IPM became the logical answer to problems arising as a result of the over-exploitation of chemical insecticides (Smith, 1969). Australia is perhaps one country where IPM was of tremendous assistance. Between 1960 and 1990, Australian cotton farmers relied so much on the unilateral use of chemical insecticides that eventually *H. armigera* became resistant to almost all recommended insecticides.

However, following a country-wide adoption of transgenic cotton, new production practices and the adoption of IPM practices, the country managed to significantly reduce insecticide use on cotton from 1,000 tonnes of active ingredient from 1998-2003 to just 50 tonnes from 2008-2013, while raising average yields of irrigated cotton from 1,200 kg/ha in the 1970s to 2,270 kg/ha today (Sustainability Report, 2014).

IPM has traditionally entailed using a combination of four tactics to manage pests:

- Cultural methods,
- Host plant resistance,
- Biocontrol agents, and
- Chemical insecticides.

This 'IPM toolbox' is currently undergoing a rapid evolution in tandem with an emerging need for new options that provide effective, economical and environmentally sound management as necessitated by a re-registration of existing insecticides; advent of new insecticides with novel modes of action; emergence of new pest species on cotton; the development and emergence of new technologies based on genetic engineering; and new tools such as drones and geographical information systems among others that may help farmers to more efficiently deal with pests (NAS, 2000). Much more could be done with 'genetic male-sterile' technologies and pheromones, but this might only be feasible on an area-wide basis, not on individual smallholder farms.

Walking the Talk on IPM

Attempts to replace the insecticide-dependent control paradigm with other methods that allow for more sustainable use of insecticides have so far achieved limited success, especially in low-income countries. Parsa *et al.*, (2014) have identified 51 potential reasons on why this has been the case. Some of the key reasons include the farmers' needs for simple solutions to apparently complex problems, while R&D institutions have not yet done enough to make them practical and efficient. Other factors include IPM's requirements for larger inputs of time and knowledge than conventional control, and the lack of adequate collaboration between governments and other institutions — notably R&D, extension services, and NGOs — on the promotion of IPM practices. Agrochemical companies have, quite naturally, not been in a position to support IPM, which seeks to minimise insecticide usage. In spite of many challenges, IPM has at least helped to promote the drive toward a more enlightened approach to pest control by encouraging the routine monitoring of pests on crops, as well as an increased consideration of multiple factors such as damage levels, pest infestation levels, and the presence or absence of natural enemies prior to making the decision to spray.

Government Policies to Increasingly Focus on Reducing Insecticide Use on Cotton

In pest-management practice, farmers will continue to overuse insecticides on cotton because there exists a basic gap between their viewpoint and that of society. While farmers tend to consider only the direct monetary costs of insecticides, society tends to add to such cost the impact of future damages from resistance and the suppression of natural enemies, as well as the cost of environmental pollution. The difference in costs has led to insecticide overuse because users of insecticides often see the cost of insecticides as being much lower than what it should be, in terms of long-term damage and pollution (Regev, 1984; Wilson & Tisdell, 2001).

Because it is virtually impossible to control the harmful effects of insecticides once they have been applied, the goal of government policies should be to significantly reduce the usage of insecticides in the first place. To that end, governments must use their influence, statutory and other powers to make the public in general and farmers in particular aware of the negative impacts of the unenlightened use of insecticides. The need by governments to re-regulate pesticide markets after the liberalisation mess cannot be over-emphasised, in light of the fact that enforcement of previous laws was ineffective and not restrictive enough on pesticide use, which allowed for increased use of unsafe, ineffective and unsustainable pest management practices.

One option that is being promoted for ensuring safe and effective use of insecticides on cotton involves the deployment of schemes that emphasize 'insecticide use exclusively by prescription'. In the USA, where a few states have adopted such schemes, it is mandatory for insecticides to be applied only after a licensed prescriber or professional pest manager has evaluated the pest problem and established that an insecticide application is indeed warranted (Whitaker, 1998). Such practices, which in the case of pharmaceuticals for human use requires designated drugs to be dispensed on a prescription basis, has helped to curb drug misuse in low-income countries. Adoption of insecticide use by prescription may hopefully help to limit some of the malpractices that are generally associated with insecticide use. However, if the introduction and ultimate adoption of these schemes in such countries is to be successful, an institutional overhaul of current systems for the provision of farmers' support services by extension, non-governmental organisations and R D institutions will be needed.

The other option for managing insecticide use entails governments using economic instruments to deliberately minimise insecticide use and thus promote the development and uptake of alternative pest control

methods. For example, in 1995, Sweden, Denmark and the Netherlands collectively passed legislation that mandated reductions of 50% or more of agricultural pesticide use in their countries by 2000. Such reductions, which were in response to public outcry about environmental pollution and the need to keep agriculture competitive, were achieved without significantly affecting crop yields (Matteson, 1995). Recently, researchers from France (Lechenet *et al.*, 2017) demonstrated that low pesticide use rarely decreases productivity and profitability in arable farms. They did not detect any conflict between low pesticide use and both high productivity and high profitability in 77% of the 946 farms examined. In many low-income cotton-producing countries where abuse of insecticides is rampant, governments can similarly adopt mandatory reductions in pesticide use by imposing taxes on pesticide imports. Such interventions would increase retail prices of chemical insecticides and hence encourage greater use of alternative non-chemical methods for pest control. Government subsidies on biological inputs for pest management would also strengthen non-chemical approaches. Cotton farmers in particular would feel compelled to spray their fields on an as-needed basis, thus exploiting cotton's ability to produce an optimal crop even after having lost some of its fruiting points, either to bollworms or through natural shedding through compensatory growth (Reed, 1965). The use of regulatory instruments such as environmental taxes or tax rebates as incentives has the potential to bring about similar outcomes (Whitaker, 1998).

Conclusion

In view of the critical importance of cotton to the agriculture-led economies in most low-income countries, the need to make cotton production sustainable and profitable cannot be over-emphasised. Because pest management is crucial for the optimisation of cotton yields, cotton stakeholders need to have a clear understanding of the implications of externalities associated with insecticide use, and how it should be minimised in the interest of the sustainability of cotton production.

To that end, cotton stakeholders in general, and farmers in particular, should be given an understanding of how cotton agro-ecosystems function, as well as how interventions such as the use of insecticides can bring about resistance, resurgence, and other side effects to both mankind and the environment. Cotton R&D institutions will need to increasingly take up training roles to ensure cotton farmers use non-chemical methods, IPM, and insecticides in a more enlightened manner. To date, training and advisory roles being undertaken by extension institutions are woefully insufficient to enable farmers get out of the growing pesticide crisis.

Because the agrochemical industry has tended to prioritise the sale of their products rather than ways their products

could be safely applied, farmers have invariably ended up being unduly exposed to pesticides. For lack of facilities needed to specifically deal with pesticide poisoning, many of the ill effects associated with exposure to highly toxic and hazardous insecticides pesticides tend to be wrongly attributed to other causes. This fact — coupled with high illiteracy rates, prevailing information asymmetries, and weak regulatory institutions — tends to worsen the situation. The need for primary health care services in order to deal with the prevention, recognition and treatment of pesticide poisoning cannot therefore be over-emphasised.

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