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# Herbicide Applied to Imidazolinone Resistant-Maize Seed as a *Striga* Control Option for Small-Scale African Farmers

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*Striga* is a major constraint to food production in Africa. Most technologies developed for the eradication of *Striga asiatica* from the United States are not adaptable to Africa. Imazapyr and pyrithiobac coated imidazolinone-resistant (IR)-resistant maize seed prior to planting at rates of 30 to 45 g ha$^{-1}$ provide near season long control of *Striga* and can increase maize yields three- to fourfold if supplied with fertilizer. Slow release seed coatings reduce maize injury when post-planting rains are sparse and improve *Striga* control when there is excessive rainfall early in the season. Models suggest that herbicide resistance may not be a significant threat in short season maize, but vigilance in removing flowering *Striga* plants that are not controlled is recommended due to the known risk of evolution of resistance to these herbicides. Stacking the IR gene with glyphosate resistance and using imazapyr treated seed and applying glyphosate mid-season would provide season long *Striga* control and delay the evolution of resistance to both herbicides. To date, adoption of this technology has been limited by a number of factors. However, it should be included as one component of a multi-factor approach to increasing maize productivity in areas of Africa where *Striga* is problematic.

**Nomenclature:** imazapyr; pyrithiobac; *Striga*, *Striga hermonthica* (Del.) Benth. STRHE; *Zea mays* L.

**Key words:** Seed coating herbicides, imazapyr-resistant hybrids, herbicide resistance, slow release herbicides.

*Striga hermonthica* (L.) Benth. or witchweed is a parasitic weed that attacks maize, sorghum, and pearl millet [*Pennisetum glaucum* (L.) R. Br.]. It has become an increasing problem to small-scale subsistence farmers in sub-Saharan Africa and represents today the largest single biological barrier to food production in the region (Ejeta 2007). Yield losses depend on the level of *Striga* infestation, the soil nutritional status, the agro-climatic conditions, the plant species, and the genotype grown (Oswald and Ransom 2004). Losses can range from 15% under more favorable conditions up to 100% when several stress factors affect the crop simultaneously. *Striga* infestations can become so severe in all major cereal producing regions of Africa that farmers will abandon their fields to cereal production and therefore large swathes of Africa will be precluded from becoming major cereal producing areas.

Remarkable progress in the eradication of the witchweed, *S. asiatica* (L.) Kuntze, in the United States has been achieved as documented in this symposium. Much of this success can be attributed to the discovery of technologies that eliminated witchweed seed production or viable seeds in the soil, or both. POST herbicides that control witchweed after emergence were identified for the numerous cropping systems common in the Carolinas where witchweed had become established. In most cases, these herbicides were focused on controlling emerged *Striga* to stop the production of new seed, rather than protecting the host crop. Furthermore, ethylene was developed as a very effective means of reducing seed banks by inducing germination of nearly all ''conditioned'' seeds in the soil from a single application. Unfortunately, few if any of the technologies that were developed and used in the United States have been adaptable to *Striga* control in Africa. The failure of these technologies to impact farmers in Africa can be attributed to both technical as well as socioeconomic reasons. Agronomic methods of *Striga* research in Africa has been recently reviewed (Ransom et al. 2007).

Most farmers in the regions of Sub-Saharan Africa where *Striga* spp. are the most problematic can best be described as small–scale, subsistence farmers. They have limited access to cash and therefore purchase few inputs. Moreover, there are often limitations on the crop rotations that these farmers can employ, as they consume much of what they produce. Cereals such as maize or sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*] form the major basis of their diet (FAOSTAT Data 2008). Herbicides are rarely used in Africa outside of South Africa and usually only in high value crops. The infrastructure that avails farm inputs including herbicides to farmers in remote areas of some countries in Africa is inadequate but has recently improved dramatically. Weeds are controlled by hand, largely with family or bartered labor, and labor costs are still relatively low compared to other purchase inputs. Prior to the development of herbicide resistant crops, dicamba was the only herbicide that offered some yield protection if applied after *Striga* attachment and before maize becomes sensitive to the herbicide (Odhiambo and Ransom 1993; Ransom et al. 1990b). Nevertheless, it was never used in Africa for *Striga* control at the farm level. Yield protection is considered to be an essential characteristic for an herbicide to be viable in Africa, as growers must recoup the cost of an input the same season that it is applied because of their limited resources. Furthermore, aside from the logistical problems of transporting ethylene, it was not particularly effective in reducing *S. hermonthica* seed banks, at least not in eastern Africa, because of the high level of dormancy of seeds (Ransom and Njoroge 1991).

The development of imazapyr and pyrithiobac seed coatings for the control of *Striga* potentially offers an effective means of controlling *Striga* with smaller amounts of herbicide than is used in spray applications (Abayo et al. 1996, 1998; Berner et al. 1997; Kanampiu et al. 2001, 2002, 2003, 2007, 2009). This technology reduces yield loss, depletes the *Striga* seed bank in the soil so subsequent *Striga* numbers are less the following year, is cost effective, and is compatible with existing cropping systems. These criteria had previously been identified as essential to the adoption of *Striga* control

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techniques by farmers (Ransom 2000). With this seed coating technology, *Striga* seeds after germination and before attachment and *Striga* seedlings that attach are controlled when the herbicide concentration in the soil or plant is adequate, thereby protecting the maize plant when it is most sensitive to parasitism.

## Basic Elements of the Technology

**Adapted Varieties with Herbicide Resistance.** The first component of this technology was the breeding of adapted hybrids or open pollinated varieties (OPVs) of maize with resistance to herbicides that inhibit acetolactate synthase (ALS). The test of concept research in Kenya was conducted with PH 3245 IR, a hybrid developed by Pioneer Hi-Bred International adapted to the southeastern portions of the United States (Abayo et al. 1996) and later validated in Nigeria (Berner et al. 1997). This hybrid had homozygous target site resistance to ALS-inhibiting herbicides. The ALS in this material originally was reported to have a mutation of tryptophan 552 to leucine, conferring high cross resistance to most ALS inhibitors (Bernasconi et al. 1995). More recently the mutation has been re-aligned to position tryptophan 574 according to amino acid numbering of the *Arabidopsis thaliana* (L.) Heynh. ALS gene sequence (Tranel et al. 2011). Although this hybrid had very good resistance to the ALS-inhibiting herbicides tested, it was poorly adapted to the mid-altitude tropics and was very susceptible to the prevalent viral and fungal diseases of the area. Experiments conducted with this hybrid were routinely treated with fungicides and insecticides to maintain some yield potential. An open pollinated maize variety was later developed by the International Maize and Wheat Improvement Center (CIMMYT) that was advanced by backcrossing ZM503, a varietal cross (INT-A/INT-B) developed by CIMMYT Zimbabwe with good adaptation to the mid-altitude regions of eastern and southern Africa with Pioneer Hybrid 3245IR as the IR donor (Kanampiu et al. 2007). A more complete description of the procedures used to develop this material is summarized by Kanampiu et al. (2003). One of the key features in the development of this material, however, was that the IR gene in PH 3245IR (Trp574) is semidominant. Herbicide resistance was expressed to lower herbicide doses in heterozygous plants but hybrids and varieties needed to be homozygous for the gene to be sufficiently resistant to tolerate the relatively high concentrations of herbicides applied to the maize seed.

More recently, four hybrids were developed by CIMMYT and allocated to three Kenyan seed companies (Kenya, Western, and Lagrotech) and the Kenya Agricultural Research Institute for commercialization and two OPVs were allocated to Western and Freshco Seed companies in Kenya. One OPV has been released in Tanzania and is under commercialization by Tanseed International.

**An Effective Herbicide Applied at the Correct Rate.** Another component of this technology is an effective herbicide. A number of herbicides with an ALS target site activity were initially screened by drenching the maize seed at a predetermined rate after planting and before the seed was covered with soil (Abayo et al. 1996). Most herbicides either caused excessive crop injury or were ineffective in controlling *Striga*, at least at the rates used (Abayo et al. 1998; Kanampiu et al. 2001). Imazapyr, an imidazolinone herbicide, at 30 to 45 g $ha^{-1}$, was the most promising for seed coating. This initial screening showed that persistence in the soil was essential for the herbicide to be effective against *Striga*. The persistence and potential for imazapyr to carryover from one season to the next is probably one reason that it is used more widely in vegetation control on noncropped land and in forestry sites and not in annual crop production in other areas of the world. Imazapyr is also relatively soluble and weakly bound to the soil allowing it to move into the root zone of the maize plant after the onset of the rains. This forms a protective zone in the upper profile of the soil around the maize seed with sufficient herbicide to control *Striga* seedlings after they germinate and attach. Additionally, imazapyr is quite mobile in the maize plant and any chemical could potentially be translocated to the other parts of the plant or exuded into the rhizosphere or translocate to attached *Striga* seedlings (Kanampiu et al. 2002). Later pyrithiobac, a pyrimidinyl(thio)benzoate (or pyrimidyloxybenzoates) herbicide, was identified as having similar activity to imazapyr and was included with imazapyr in developmental research (Kanampiu et al. 2002, 2003). Recent commercialization processes have focused on imazapyr as it was registered for this use.

At the currently recommended rate of imazapyr of 30 to 45 g $ha^{-1}$, crop safety can be a concern if rainfall is sparse after planting. If rains are heavy, however, the herbicide can be moved beyond the root zone too quickly due to weak adsorption on soil, precluding season long control (Kanampiu et al. 2007). These factors are part of the reason that *Striga* control and maize yield improvement with this technology can at times be erratic (Kanampiu et al. 2003). The persistence of imazapyr has the potential for a residual toxic effect on subsequent susceptible crops, though in the tropic environments of Africa where this research was conducted, no residual toxicity was ever noted. Given the relative mobility of imazapyr in the soil, there is the potential for the imazapyr that is not degraded to move off-site when rainfall is excessive and have an adverse effect on the environment.

**Applying the Herbicide to the Seed.** Imazapyr and pyrithiobac can control *Striga* when applied as a broadcast or foliar application to maize plants (Kanampiu et al. 2001, 2002). Nevertheless, the timing of these applications is critical and most effective if applied shortly after the main flush of *Striga* plants has attached to the maize roots. *Striga* attachment timing depends on the amount of rainfall and the timing of rainfall relative to the germination of the maize plant. A broadcast application of imazapyr offers broad spectrum weed control while seed coating of the herbicide only controls *Striga*, while all other weeds need to be removed by hand. Initial research suggested that *Striga* control was less effective when imazapyr was applied to foliage relative to being point placed in the soil near the seed at the same per ha rate (Abayo et al. 1998; Kanampiu et al. 2001). This is possibly due to the concentration of the herbicide being less in the root zone of the maize plants when adventitious roots develop and move outward in the soil at the time that *Striga* seed are conditioned and susceptible for germination and attempt attachment.

Commercial seed is usually dressed with fungicides or insecticides in most regions of the world. Herbicides, however, have never previously been commercially applied via seed coating, although herbicide protectants are often applied to sorghum seed (e.g., Hirase and Molin 2001). Dawson (1987) applied the herbicide EPTC to maize seed to incorporate the herbicide into the soil, but this was never commercialized. There had been two earlier attempts to apply herbicides to seeds of crops having metabolic resistance to herbicides for control of the related root *Orobanche* spp. parasites. Jurado-Exposito et al. (1999) applied imazethapyr to pea seeds to control *Orobanche crenata* Forssk., and Diaz-Sanchez et al. (2003) applied pronamide to sunflower seeds for *Orobanche cumana* Wallr. control. In both cases the control was for too short a period to be commercialized.

The magnesium salt of imazapyr was the safest form and was used in most of the early development work. Later it was found that the free acid worked as effectively. Incorporating imazapyr into the seed by dissolving the herbicide in water and allowing the seed to imbibe the solution provided good *Striga* control but was too phytotoxic and difficult to commercialize to be a viable means of applying the herbicide (Kanampiu et al. 2001). The process of soaking seeds in water for a day and then drying them before planting is referred to as priming and has been shown to be beneficial in some situations (Murungua et al. 2004). Seed coating with imazapyr mixed with polyvinylpyrrolidone (PVP) and a commercially available seed coating dust, Murtano™ (containing 20% ai lindane and 26% ai thiram), were less phytotoxic than priming while providing good *Striga* control. Seed coating with imazapyr mixed with the Murtano™ dust only was slightly safer to the maize seed than PVP. Because Murtano™ is also commercially available in Kenya, it became the medium of choice for applying imazapyr to maize seeds in subsequent research and commercial applications in Kenya.

Slow release formulations were proposed to overcome poor stand establishment due to high concentration of herbicide during germination and early establishment of the crop, especially when rainfall is scarce during this period. Slow release formulations could also be valuable when rainfall is too plentiful and would wash the herbicide out of the root zone, as well as for late-maturing maize where a longer period of protection is imperative to prevent *Striga* seed set. Several slow release formulations were synthesized based on binding imazapyr to high capacity anion exchangers and using them to coat maize seed. The best seems to be a polyethyleneimine gel (Kanampiu et al. 2009). Epidemiological field data from a multitude of sites support the conclusion that the slow release formulations increased stand establishment across sites and seasons compared to the control when there was low rainfall (Kanampiu et al. 2009). There are not yet sufficient data that demonstrate that the higher rates of imazapyr that can be applied safely with a slow release seed coating to provide more consistent or longer season *Striga* control. Such data will be necessary for this to be considered a viable single herbicide solution for long season-long control in maize. The use of higher rates could increase the possibility of *Striga* resistance development to imazapyr as a result of greater and stronger selection pressure.

To this end, the partners have continued to optimize both the slow release compositions and the potential for incorporating multiple crop protection compounds in the coat. Coating strategies based on waxy alkylamines allow long-term release of both herbicides such as imazapyr, fungicides such as azoxystrobin, and insecticides such as imidacloprid simultaneously (Burnet et al. 2010). These coating materials are more adhesive and less dusty, which should allow more uniform levels on the seed. These materials also have significant potential for application by the seed in the hill at planting if this was ever to become an accepted strategy. Provision of multiple protection modes via this route would hold potential to deal with a range of issues in early germination in a fairly simple manner.

**Alternatives to Seed Coating: Herbicide Pellets.** The process of seed coating with herbicide, segregating treated IR-maize from conventional maize seed, and dealing with unsold seed that has already been treated with herbicide are issues that have impeded the marketing of herbicide treated IR-maize in Africa. Many African seed companies are relatively small and do not have large cash reserves to enable capital investment in seed coating equipment. This, of course, raises the issue of whether the herbicide can be safely provided to farmers with the seed but in a separate package. Although there are inherent risks in separating the herbicide from the resistant seed at the marketing level, there are also several advantages. Firstly, an herbicide pellet to be planted with the seed allows some degree of dose control—for example, smaller or fewer pellets for the short rains, larger or more pellets for the long rains. Secondly, pellets offer a more exact dose than a coat. Third, pellets are able to provide longer exposure than a coat. Finally, color coding of seed with harmless dyes may be a more general means of identifying the IR product and would be easier to apply in a simple seed treatment facility than an herbicide. Such a color code can, of course, be linked to the color of the protective pellet.

## Combining Herbicide Resistance with Field Resistance

Developing maize genotypes with field resistance to *Striga* would be an ideal solution to the *Striga* problem. Differences between OPVs and hybrids in the number of *Striga* plants supported and the yield under *Striga* infestation have been reported (Oswald and Ransom 2004; Ransom et al. 1990). In general terms, this observed field resistance has been marginally effective and unstable. Some level of polygenetic resistance has been incorporated into maize genotypes adapted to major West African environments by the maize breeding program at the International Institute of Tropical Agriculture (Menkir et al. 2007). Recently inbreds and hybrids with this polygenic field resistance and the IR genes have been developed (Menkir et al. 2010). These hybrids sustained less damage symptoms and yield loss under *S. hermonthica* infestation and supported fewer emerged parasites than the susceptible hybrid check. Also, imazapyr-coated seeds of these hybrids planted under *S. hermonthica* infestation sustained either no or less than 20% yield loss and supported very few emerged parasites. Moreover, these IR hybrids may be planted without imazapyr seed coating in infested fields at certain intervals to delay the development of high levels of resistance to imazapyr.

## Delaying Herbicide Resistance in *Striga*

Resistance to ALS inhibiting herbicides such as imazapyr has evolved quickly in many weeds species where herbicides



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with this mode of action are used repeatedly. Models initially predicted that *Striga* resistant to imazapyr would evolve quickly and that there would be five resistant *Striga* plants surviving the seed treatment technology per ha per year (Gressel et al. 1996). Since no obvious surviving *Striga* plants appeared in the research plots that had been treated with this technology for several seasons or later in any of the widespread field testing, some of the assumptions used in the initial model were probably incorrect. Observation during the development of the IR-maize materials showed that maize must be homozygous for the resistance gene. The assumption was subsequently altered so that homozygosity would also be required in *Striga* before it would be resistant to the relative high concentration of herbicide around the seed of the maize plant. The new prediction based on the need for homozygousity in maize and the lack of resistance in the field was that resistance would be exceedingly rare and that only five resistant plants would survive each year per million ha of treated land (Gressel 2005), as long as enough herbicide persists to control to a level that only homozygously resistant individuals can persist. This prediction suggests a minimal risk with the evolution of resistance in short season maize. One might question whether this prediction is correct for other point mutations that confer a higher level of resistance to imidazolinone herbicides (Tranel et al. 2011), and perhaps a heterozygote with a different point mutation might survive. As no resistance has yet evolved in the field, despite the massive *Striga* seedbank, and the large areas treated, the best conclusion seems to be that the levels of herbicide near the maize seed are so high as to require homozygosity of all point mutations to survive, despite the fact that some mutations are more resistant than the one used. In long season maize, the herbicide could dissipate to a level that allows heterozygous individuals to emerge and flower (especially the more imidazolinone resistant point mutations). If that occurs, heterozygous (Aa) by heterozygous (Aa) individuals will cross, and one-fourth (25%) of the progeny will have homozygous resistance (AA) and the technology could quickly fail. Additionally, *Striga* plants in long season maize that evolve heterozygous resistance with different point mutations could similarly recombine, conferring a high level of resistance. Thus, it is prudent to assume that resistance will evolve in long season maize with the present mutation if this is the only control practice employed. Perhaps it would be advisable to use a more resistant mutation in maize bred for long-season use, together with slow release formulations that would keep the herbicide at a high and optimal level in the right position in the soil profile for a longer period.

Stringent field monitoring by farmers for early flowering *Striga* plants that might be resistant and rouging them by hand could help prolong the utility of this technology by many years. Additionally, genetically modified (GM) crops are increasingly likely to be accepted in Africa, and crop herbicide resistance is one of their major traits (James 2010). Glyphosate resistant maize is already successfully used in South Africa. Therefore, glyphosate sprayed in-crop on herbicide resistant GM maize could be another strategy that will control *Striga*, along with other weeds (Joel et al. 1995). Perhaps glyphosate could also be applied as a seed dressing for *Striga* control (Gressel and Joel 2000). Stacking IR resistant genes and glyphosate resistant transgenes in the same hybrids could greatly expand options available to farmers and provide options that could greatly prolong the evolution of resistance to either herbicide (Gressel 2009).

## Testing On-Farm and Farmer Evaluation and Market Potential

New technologies being developed should be tested on-farm, under researcher- as well as under farmer-managed conditions before general dissemination. This allows for an analysis of their technical and economic efficiency and provides an opportunity for farmers to evaluate the new technologies for the criteria they find important. Therefore, a set of trials, surveys, and farmer evaluations were conducted in western Kenya, parallel to the development of IR-maize.

First, the performance of IR-maize developed with the ALS gene mutation from the Pioneer Hi-Bred source described previously was compared to a conventional maize hybrid in on-farm researcher-managed trials in 2002. IR-maize showed good *Striga* control and a dramatic yield increase of 2,400 kg $ha^{-1}$ (from 1,300 to 3,700 kg $ha^{-1}$) (De Groote 2007). In 2004, another set of on-farm trials that were farmer-managed compared IR-maize to the farmers' preferred variety in three districts (similar to counties within states in the United States). Imazapyr applied to IR-maize showed good *Striga* control and increased yield in two districts, but not in the third one (Vihiga), likely because of heavy rains that might have washed off the herbicide (De Groote 2007). The yield increase from IR-maize seed was estimated at 500 kg $ha^{-1}$, consisting of a germplasm effect of 370 kg $ha^{-1}$ and an herbicide effect of 130 kg $ha^{-1}$. With maize prices then at US\$0.202 $kg^{-1}$, seed prices at US\$34 $ha^{-1}$, and herbicide cost at US\$4 $ha^{-1}$, the overall marginal rate of return (MRR) was 2.4 (good), with an MRR of 1.9 (respectable) for the germplasm and an MRR of 5.6 (very good) for the IR-maize technology.

A survey of 57 farmers who participated at the field days showed that they generally appreciated the technology. Moreover, most respondents (90%) indicated that they would be interested in buying the seed at the same price as conventional maize seed, although to a lesser extent (61%) in Vihiga district, where IR-maize did not do well. Their interest, however, was dependent on price: only 59% would buy IR-maize at a 10% premium, and only 15% in Vihiga.

In another set of trials, IR-maize was incorporated as one of many technology options in evaluating different cropping systems over six seasons. The options, selected after extensive discussions between scientists and farmers, included the "push–pull" system (this system was initially designed to push stalk borers from the maize by planting an intercrop of *Desmodium* spp. between the rows and surrounding the field by Napier grass [*Pennisetum purpureum* K. Schum] in order to pull them away from the maize), soybean [*Glycine max* (L.) Merr.] and *Crotalaria* spp. rotations, either with IR- or local maize, and supplemented or not with fertilizer (Vanlauwe et al. 2008). Farmers indicated that their most important criterion to evaluate cropping system long-term was yield, followed by soil fertility enhancement and *Striga* resistance; minor criteria were labor saving and stem borer resistance (De Groote et al. 2010b). At regular intervals, farmers were invited to evaluate all treatments for all criteria and give them an overall evaluation. IR-maize was generally appreciated in the cropping systems but not as a mono-crop. The most preferred cropping system was push–pull with IR-maize and fertilizer, followed by the rotation systems with *Crotalaria* and soybeans, especially with IR-maize and fertilizer. In monocropping systems, however, IR maize was only appreciated in combination with fertilizer and in only 2004 (De Groote et al. 2010b).

The economic analysis of these same trials, using marginal analysis with a multi-output, multi-period model, show that the push–pull and soybean rotations were highly profitable (De Groote et al. 2010a). Push–pull was more profitable although it requires a relatively high initial investment cost. IR-maize, like green manure rotation and fertilizer, all increased yields, but these investments were generally not justified by their increased revenue. In particular, the yield advantage IR-maize over the control was disappointingly low.

To help extension agents and seed companies in developing appropriate dissemination strategies, the market potential for this technology was analyzed by combining different data sources into a Geographic Information System. Superimposing secondary data, field surveys, agricultural statistics, and farmer surveys made it possible to clearly identify the *Striga*-prone areas in western Kenya (De Groote et al. 2008). Results indicated that *Striga* affects a maize area of 246,000 ha annually in this region of Kenya, with a population of 6.4 million people and a maize production of 580,000 tons, or 81 kg person$^{-1}$. Population density in this area is high at 359 persons km$^{-2}$. A survey of 123 farmers revealed that 70% of them have *Striga* in their fields. A contingent valuation survey indicated that farmers would, on average, be willing to buy 3.67 kg of the IR-maize seed each at current seed prices, sufficient to sow 44% of their maize area. By extrapolation over the maize area in the zone, total potential demand for IR-maize seed is estimated at 2000 to 2700 tons annually. Similar calculations for sub-Saharan Africa, but based on much less precise data and expert opinion rather than farmer surveys or trials, estimate the *Striga*-infested maize area at 6.1 million ha and the potential demand for IR-maize seed at 153,000 tons (De Groote et al. 2008). Another estimate, however, puts the *Striga*-infested maize area at 2.4 million ha (Woomer et al. 2008).

## Dissemination and Adoption of the Technology

As with any new technology, farmers must learn about it, try it, have access to it, and determine that it will enhance their profits and productivity before it will be adopted. Since herbicides are rarely used in small-scale farms, there is no tradition of purchasing and employing an herbicide for weed control. Creating awareness of a relatively radical technology was the first challenge of getting this technology into the hands of farmers. In the past, information about *Striga* and its control was largely obtained, in the case of Kenya, from government extension services or from other farmers (Oswald 2005), with less than 25% of the farmers obtaining information from other sources. To focus awareness on this new technology, a multi-partnership of farmers, seed companies, nongovernmental organization, extension agents, and research organization conducted over 10,000 on-farm demonstrations (Kanampiu et al. 2007).

IR-maize treated with imazapyr was adopted as an important extension recommendation by the African Agricultural Technology Foundation (AATF), who then organized large scale demonstrations and over a 6-yr period, assisting farmers in testing this technology beginning in 2005 in more than 60,000 farm locations in western Kenya. Seed production and commercial sales of 2.5 tons of the IR-maize hybrid ''Ua Kayongo'' occurred in 2009. Western Seed commercialized 11 tons of ''WS 303,'' an IR-maize OPV in 2010, and 40 tons were available in farmer accessible shops for the 2011 season. Though the dissemination process is still in its infancy, the adoption of this technology by those that have been exposed to it has been disappointing. This poor adoption can be attributed to many factors. Seed production and availability by commercial seed companies has been erratic for reasons previously described. The IR-maize hybrids have not always been competitive for yield compared to other commercially available hybrids in the absence of *Striga*. If the hybrid or OPV used does not yield more than non-IR commercial materials in the absence of *Striga*, this technology will not show any advantage if *Striga* pressure is minimal. Because predicting *Striga* levels is not always possible, even in fields that are nominally considered infested by *Striga*, consistently demonstrating the value of this technology is difficult. Furthermore, farmers in the parts of western Kenya most affected by *Striga* may not buy hybrid seed every year and therefore must plan for funds needed to purchase seed.

Further, the IR-maize technology was never considered as a standalone technology, since soil fertility is often as limiting or more limiting than *Striga* in many areas where *Striga* is problematic. Moreover, IR-maize can be an effective component of a multi-factor approach to *Striga* control and improved productivity as it offers the advantage of providing yield enhancement the first season, whereas the rotations and other practices that focus on the reduction of seed numbers in the soil impact *Striga* levels and yield only after one or more cropping seasons. Because farmers purchase few agricultural inputs, the lack of nearby shops that would stock IR-maize may be a constraint to the movement of this technology particularly for farmers who do not live relatively close to larger towns. Recently there has been a concerted effort to increase the number of shops that stock agricultural inputs that may alleviate this problem in some countries in Africa. Storage conditions also impact the long-term viability of treated maize seed in most existing retail shops.

## Lessons Learned

Many farmers with serious *Striga* infestations who have tested this technology have been very enthusiastic about it, as it is well adapted to their current farming practices and doesn't require any special skills or knowledge to use. The lack of a seed system that will provide high quality seed properly coated with imazapyr is currently the major constraint to widespread dissemination of this technology. Perhaps seed companies have not filled this niche due to the lack of sufficient margins to motivate commercial interest. This should change due to rising maize prices due to part of the world's maize production going to ethanol.

Feedback during the early stages of commercialization indicate that IR-maize hybrids/OPVs must have similar or higher yield potential in the absence of *Striga* to be readily adopted by farmers. Furthermore, most local seed companies are not able to absorb the risk associated with introducing a new technology, lack the initial capacity to prefinance seed production, and to develop separate herbicide treatment and seed storage facilities. Subsidies may be needed to ensure treated seed availability in the short term to help cover the

Table 1. Timeline for the development and dissemination of IR-maize technology for *Striga* control in Kenya.

| Activity | Start date | End date |
|---|---|---|
| Inducement, discovery, and incorporation of IR[a] gene into a stable maize inbred | ? | ~1988 |
| Backcrossing the IR gene and development of a commercial IR-maize hybrid adapted to the United States | ~1989 | ~1992 |
| Determining the efficacy and safety of ALS-inhibiting herbicides on *Striga* in the United States | 1993 | 1994 |
| Determining the potential efficacy and crop safety of point applied ALS-inhibiting herbicides for *Striga* control in Kenya | 1995 | 1996 |
| Developing and optimizing techniques for applying herbicide to maize seed for *Striga* control (laboratory and greenhouse) | 1996 | 1997 |
| Initial field testing of seed treatments | 1997 | NA |
| Multi-location field testing using maize genotypes with some tropical background | 1998 | 2001 |
| Development and commercial release of adapted IR-maize OPVs and hybrids | 1998 | 2005 |
| Development of slow release herbicide seed treatments | 2005 | On-going |
| Commercial availability of first IR-maize hybrid in Kenya | 2009 | NA |
| Dissemination of commercially available technology | 2009 | On-going |
| Commercial availability of first IR-maize OPV | 2010 | NA |

[a] Abbreviations: ALS, acetolactate synthase; IR, imidazolinone resistant; OPV, open pollinated variety.

added cost of treatment and segregation storage facilities and to participate in disseminating this technology.

The development and dissemination of this technology in Africa has been a relatively slow process (Table 1) for several reasons. First, at the initial stage there were very few resources devoted to the required basic research. Since *Striga* is a prohibited species in the United States, all of the field and laboratory work had to be done in Africa and all the research was done by a single research group. Ultimately, the lack of IR-maize genotypes adapted to eastern Africa was probably the most limiting factor in the process. More resources should have been devoted to the development of IR-hybrids and OPVs at the outset. The buy-in of commercial seed companies in the development of these materials at an early stage might have hastened the process.

We have also learned that it requires massive human resources to educate farmers on a new technology such as this. This is partly because of the large number of farmers in Africa and their small farm size compared to the developed world where one farmer may farm 1,000 ha or more, and partly because of the educational level and experience with changing technologies of farmers in Africa. Another sign of the utility and success of the technology is its adaption to sorghum in a very similar manner (Tuinstra et al. 2009).

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