academicJournals

Vol. 8(11), pp. 492-506, November 2014
DOI: 10.5897/AJPS2014.1186
Article Number: 340D9F448876
ISSN 1996-0824

http://www.academicjournals.org/AJPS

African Journal of Plant Science

Review

Advance research on *Striga* control: A review

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Received 4 April, 2014; Accepted 10 November, 2014

The parasitic weed–(Striga spp.), is a major biotic constraint and a serious threat to subsistence cereal crop (sorghum, maize, pearl millet, finger millet and upland rice) production in sub-Saharan Africa. Severity of the parasitic weed in this area is aggravated by the inherent low soil fertility, recurrent drought and overall natural resource degradation. *Striga hermonthica* (Del.) Benth. and *S. asiatica* (L.) Kuntze are the major biotic constrains to crop production, especially in the non-fertile semi-arid region of Africa, whereas *S. aspera* (Willd.) Benth. and *S. forbesii* Benth. are of lower economic importance. Striga produces numerous minute seeds, which can remain dormant in the soil for as long as up to 20 years. Yield losses due to Striga damage range between 20-80% in Africa but total crop failure is possible in the worst situations. A review of these findings has been discussed for the benefit of poor-resource farmers. Based from these findings, different control measures has been recommended in tackling the negative effects of this weed. Striga can be managed using one or more methods: use of cultural and mechanical control practices, nitrogen fertilizers, push pull technology, biological control practices, resistant host crops, use of herbicides and integrated Striga control methods. However, an integrated Striga management strategies suitable approach, a combined use of two or more control measures, is required to achieve success against this pernicious weed.

Key words: *Striga* spp., host crops, crop losses, control methods.

INTRODUCTION

Striga spp. (witch weed), a root parasitic flowering plant, is common in sub Saharan Africa (SSA) causing severe constraints to crop production. It survives by diverting essential nutrients, which are otherwise taken up by cereal crops such as sorghum (*Sorghum bicolor* [L.]), pearl millet (*Pennisetum glaucum* [L.]), finger millet (*Eleusine coracana* [L.] Gaertn), maize (*Zea mays* [L.]) and upland rice (both *Oryza glaberrima* [Steudel] and *O. sativa* [L.]) (Rodenburg et al., 2006; Atera et al., 2011). These cereals are of utmost significance to African farmers for their home consumption. Underground the weed siphons water and nutrients for its growth, while above the ground, the crop withers and grain yield is reduced (Khan et al., 2007).

'*Striga*' is the Latin word for 'witch'. *Striga* is known as witch weed because plants diseased by *Striga* display stunted growth and an overall drought-like pheno type long before *Striga* plants appear. Some local names to Striga are; in west Kenya, farmers' refer to it as Kayongo (Luo), Oluyongo (Luhya), and Imoto (Teso). In Tanzania it

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is known as Kiduha in Kiswahili and in Ethiopia such as, ‘Akenchira’, ‘Metselem’ and others (Fischer, 2006).

Striga species are obligate hemi-parasite plants that attach to the root of their host to obtain water, nutrients and carbohydrates (Van Ast, 2006). Crop yield loss due to *Striga* attacks can vary depending on *Striga* seed density, soil fertility, rainfall distribution, the cereal host species and variety grown.

In total, 25 African countries reported *Striga* infestations in 2005 (De Groote et al., 2008). *Striga* affects the life of more than 100 million people in Africa and causes economic damage equivalent to approximately 1 billion $US per year (Labrada, 2008; Waruru, 2013). It infects important cereal crops such as maize, sorghum, pearl millet, finger millet and upland rice, causing devastating losses in yields in sub-Saharan Africa, thereby limiting food supply in many developing countries (Joel 2000; Scholes and Press 2008). Farmers have reported losses between 20% and 80%, and are eventually forced to abandon highly infested fields (Atera and Itoh, 2011). Grain yield losses even can reach 100% in susceptible cultivars under a high infestation level and drought conditions (Haussmann et al., 2000). According to estimates by Gressel et al. (2004), 17.2 million ha (64% of the total area) of sorghum and pearl millet production in west African are infested with *Striga*.

The infestation area and level are expected to increase in the future, because of continued cereal monoculture in combination with low organic and mineral fertilizer input rates. *Striga hermonthica* (Del.) Benth. and *S. asiatica* (L.) Kuntze are the major biotic constraints to crop production, especially in the non-fertile semi-arid region of Africa, whereas *S. aspera* (Willd.) Benth. and *S. forbesii* Benth are of lower economic importance (Haussmann et al., 2000). Controlling *Striga* has therefore become an huge task considering the seed production rate of 10,000 - 100,000 seed/plant which remain viable in the soil for up to 20 years (Ikie et al., 2006). This can lead to seed shed rates of over 1,000,000 seeds per square meter per year (Kroschel and Müller-Stöver, 2004). This can lead to a rapid buildup of the seed bank in the soil, once fields have been contaminated (Van Mourik et al. 2008).

Research on *Striga* control has been carried for a long time and a wide range of technologies have been developed (Atera et al., 2011). Despite efforts made to control the *Striga* problem, it has persisted and increased in magnitude. Although research on the parasitic weed has a long history, adoption of the control options is limited (Emechebe et al., 2004). This is one of the greatest tests to be addressed by researchers as to why farmers are not embracing the control mechanisms.

There is so need to adopt a farming systems approach for the development and implementation of integrated *Striga* management strategies. The main objective of this review paper is to document recent and alternative options in research findings to *Striga* control methods.

ORIGIN, OCCURRENCE AND DISTRIBUTION OF *STRIGA*

Plants belonging to genus *Striga* (Scrophulariaceae) comprise obligate root parasites of cereal crops that inhibit normal host growth via three processes, competition for nutrients, impairment of photosynthesis (Joel, 2000) and a phytotoxic effect within days of attachment to its hosts (Gurney et al., 2006).

Striga are generally native to semi-arid, tropical areas of Africa, but have been recorded in more than 40 countries (Ejeta, 2007; Vasey et al., 2005). *Striga* possibly originates from a region between the Semien Mountains of Ethiopia and the Nubian Hills of Sudan (Atera and Itoh, 2011). This region is also the birthplace of domesticated sorghum (*Sorghum bicolor* L.).

Approximately 30 *Striga* species have been described and most parasitize grass species (Poaceae). *Striga gesnerioides* (Willd.) Vatke is the only *Striga* species that is virulent to dicots (Mohamed and Musselman, 2008). Among the 23 species of *Striga* prevalent in Africa, *Striga hermonthica* is the most socio-economically important weed in eastern Africa (Gressel et al., 2004; Gethi et al., 2005). Occurrences of *S. hermonthica* have also been reported from south-east Africa. *S. hermonthica* is particularly harmful to sorghum, maize and millet, but is also increasingly being found in sugarcane and rice fields (Atera and Itoh, 2011). Upland rice is becoming more and more important for African agriculture, not least because it can sustain more people per crop area than can maize or sorghum (Atera and Itoh, 2011).

Crops previously unaffected by *Striga* are now showing serious infestation. *Striga* is, therefore, fast becoming a pandemic of serious proportions in Africa because of its vast geographic spread and its economic impact on millions. The enzyme systems of the parasite thrive under low soil fertility and moisture stress conditions, where most soils have been depleted of fertility through removal of organic matter and limited use of manure. It’s low fertility in combination with drought induced stress and susceptible host cropping that predisposes the area to *Striga* (Fasil, 2002).

STRIGA CONTROL METHODS

The most and the recent control methods of *Striga* seem as follows:

Cultural and mechanical control methods

A number of cultural practices have been recommended for *Striga* control such as crop rotation (Oswald and Ransom, 2001); intercropping (Udom et al., 2007); transplanting (Oswald et al., 2001); soil and water management (Fasil and Verkleij, 2007); use of fertilizers (Jamil et al., 2011); and hand weeding (Ransom 2000) to reduce the production of further *Striga* seed. These methods should also reduce the density of *Striga* seeds already in the soil seed bank (Fasil and Verkleij, 2007). Some of these practices improve soil fertility, which will stimulate the growth of the host but also adversely affects germination, attachment and subsequent development of the juvenile *Striga* plants (Fasil and Verkleij, 2007). However, this approach has only limited success for small-scale farmers, largely due to socio-economic and financial constraints.

Hand-weeding and Sanitation

Today the most used control method against *Striga* is hand weeding. It is recommended to prevent seed set and seed dispersal. Weeding the small *Striga* plants is a tedious task and may not increase the yield of already infected plants, it is necessary to prevent seed production and reinfestation of the soil. Due to high labour costs in repeated hand-pulling of *Striga*, it is recommended that hand pulling should not begin until 2-3 weeks after *S. hermonthica* begins to flower to prevent seeding (Parker and Riches, 1993). New shoots may sprout out below the soil from infected plants requiring a second weeding before crop maturity. Sanitation consists of taking care to note infested areas and to isolate them. Seeds in the soil can be spread by wind, rainwater, plowing, and soil on tools or root crops. Seed pods on *Striga* plants attached to maize or sorghum plants pulled for forage will infest manure and feeding areas (Parker and Riches, 1993). Crop stubble should also be uprooted or burned to prevent the continued growth and seeding of the parasite (Ramalah, Parker, Vasudeva, and Musselman, 1983). This weed competes for water and nutrients as a root parasite. In so doing, crop growth is stunted and yields are generally reduced (Ayongwa et al., 2010).

It is not practical to hand weed dense infestations, and weeding is often ineffective, particularly since it is time consuming and labor-intensive (Parker and Riches, 1993). It is practical, at a low level of infestation before *Striga* flowers and in combination with herbicides or fertilizer.

Crop rotation

Crop rotation of infested land with non-susceptible crops or fallowing is theoretically the simplest solution. Rotation with non-host crops interrupts further production of *Striga* seed and leads to decline in the seed population in the soil. The practical limitations of this technique is required more than three years for rotation. The choice of rotational crop should therefore be based 1st on its suitability to the local conditions and only secondarily on its potential as a trap crop (Parker and Riches, 1993).

Rotating the infested maize or sorghum areas to wheat/barley, pulses, or groundnuts are viable and effective options in Ethiopia. In Ethiopia two years of cropping to a non-host was reported to reduce *Striga* infestation by 50% (Shank, 2002). In the Sahel, the results of a four year experiment in bush fields indicated that one season cowpea in 1998, had a positive effect on subsequent millet grain yields, soil organic carbon and nitrogen, and reduced *Striga* infestation. The increase in yields due to millet-cowpea rotation was 37% in 1999 compared to three to five years continuous millet cropping (Samake, 2003). However small-holder farmers desiring to maximize the grain production potential of their land may be difficult to be persuaded to grow other crops. Practical control measures are effective when a combined program of crop rotation, weeding, sanitation and, resistant varieties is included.

Trap crops and catch crops

Trap crops: Trap-crops cause suicidal germination of the weed, which reduces the seed bank in the soil. Some varieties of cowpea, groundnut and soybean have potential to cause suicidal germination of *S. hermonthica* and improve soil fertility (Carsky et al; 2000; Schulz et al., 2003).

The use of trap crops such as soybean causes suicidal germination of the *Striga* seedlings which do not attack the soybean consequently; the *Striga* is ploughed off before flowering thereby reducing the seed density of *Striga* in the soil (Umba et al., 1999). In IITA, about 40 lines of soybean were screened for their ability to induce *Striga hermonthica* seeds to germinate using the cut roots of soybean plants. The results showed variability among the soybean lines in their ability to stimulate seed germination. Hess and Dodo (2003) also found that the use of leguminous trap crops that include varieties of groundnut (*Arachis hypogaea*), soybean (*Glycine max*), cowpea (*Vigna unguiculata*), and sesame (*Sesamum indicum*) stimulate the suicidal germination of *Striga* is another technology to control *Striga*. De Groote et al. (2010) found that soybean triggers suicidal germination of *Striga* and reduces the *Striga* seed bank in the soil when intercropped with maize.

Catch crops: Catch crops are planted to stimulate a high percentage of the parasite seeds to germinate but are destroyed or harvested before the parasite can reproduce. A thick planting of Sudan grass at 20-25 kg seed per hectare should be sown and either ploughed in or harvested for forage at 6-8 weeks before *Striga* seeds. The main crop could then be planted during the main rains (Parker and Riches, 1993). From the available studies, it can be concluded that trap crops should be cultivated for at least three consecutive years in order to reduce parasite seeds (Esilaba and Ransom, 1997).

Pasture legumes; *Mucuna gigantica, Stylosanthes guyanensis* and *Desmodium* spp. were investigated for their ability to induce germination of conditioned *S. hermonthica* seed, for their effect on *Striga* attachment and on *Striga* shoot emergence. Laboratory experiments showed that the root exudates of the legumes stimulated up to 70% more *Striga* seeds to germinate than exudates of maize. Maize-Mucuna combination had the highest number of attachments while all other combinations and maize planted in pure stand had lower numbers of attached *Striga*. Cowpea varieties, cv. Blackeye bean and cv. TVU 1977 OD, produced potent exudates, which were highly compatible with sorghum as intercrops in field trials (Fasil, 2002).

In other research findings also reported the effectiveness of the combined use of trap-cropping, fertilization and host plant resistance to control *S. hermonthica* (IITA, 2002; Tesso, et al., 2007).

Intercropping

Intercropping cereals with legumes and other crops is a common practice in most areas of Africa, and has been reported as influencing *Striga* infestation. Intercropping is a potentially viable, low-cost technology, which would enable to address the two important and interrelated problems of low soil fertility and *Striga* (Fasil, 2002). Growing of sorghum in association with cowpea and haricot bean was effective against *S. hermonthica* and produced significantly improved yield per unit area in preliminary trials in Ethiopia. Intercropping had rather detrimental effect on yield performance of sorghum and showed two cowpea varieties - cv. TVU 1977 OD and cv. Blackeye bean produced the highest supplemental yield of up to 329 and 623 kg ha^{-1} grain and 608 and 1173 kg ha^{-1} biomass at Adibakel and Sheraro (Tigray, Ethiopia) in 1999 and 2000, respectively (Fasil, 2002).

Recent result shows that intercropping maize with cowpea and sweet potato can significantly reduce the emergence of *Striga* in Kenya (Oswald et al., 2002). In Kenya, more recently, it was discovered that inhibition of *Striga hermonthica*, was significantly greater in maize-silver leaf [*Desmodium uncinatum* (Jacq.) DC.] intercrop than that observed with other legumes, for example, sun hemp (*Crotolaria* spp.), soybean or cowpea (Khan *et al.* 2000). Consequently, the yield of maize was significantly increased by two tons per ha. *Disodium* species are legumes that can easily be controlled by regular cutting in order to avoid or minimize the competition with the crop if any.

The mechanisms by which *D. uncinatum* reduce *Striga* infestation in intercropping was found to be the allelopathic effect inhibiting the development of haustoria of *Striga* (Khan *et al.* 2001). Identification of the compounds released from *D. uncinatum* involved in the suppression of the parasite may give more exploitation for developing reliable intercropping strategies, as well as new approaches for molecular biology in *S. hermonthica* (Gressel, 2000).

According to Khan et al. (2007), intercropping different legumes with maize and sorghum helps reduce *Striga* but does not eliminate the weed. This explains why, in spite of most farmers intercropping cereals with legumes as the dominant cropping system in western Kenya, *Striga* infestation is still high in most fields. A variant of intercropping system dubbed “push-pull” where Desmodium spp. is intercropped with cereals with an edge of fodder crops is effective in *Striga* management. There is therefore need to combine more than one strategy to improve the effectiveness of existing control strategies (Ejeta and Gressel, 2007).

Soil fertility

Nitrogen and phosphorus deficiency as well as water stress accentuate the severity of *Striga* damage to the hosts. *Striga* is particularly a pest of low fertile soil and usually the infection decreases if mineral nutrients, especially nitrogen and phosphorus, are applied in sufficient quantities (Adagba et al., 2002).

Fertilizer application had significant effect on height, vigour score, reaction score of sorghum as well as shoot count, days to emergence, dry matter of production and dry weight of *Striga*. The application of high nitrogen (N) increases the performance of cereal crops under *Striga* infestation. This is due to the fact of that nitrogen reduced the severity of *Striga* attack while simultaneously increasingly the host performance (Lagoke and Isah, 2010).

Results of an experiment, designed to develop integrated nutrient management strategy, confirmed that the combined use of 41 kg N/ha and 30 t/ha of manure could lead to significant reduction in infestation and considerable increase in sorghum yield (Esilaba et al., 2000). Esilaba et al. (2000) and Gacheru and Rao (2001) also found that increasing soil fertility not only stimulates the growth of the host but also adversely affects longevity of the seeds in the soil, germination and attachment.

Shank (2002), has been noted in western countries that host plant shading can restrict *Striga* growth when generous soil fertilizer is applied Table 1.

Application of high dosage of nitrogen fertilizer is generally beneficial in delaying *Striga* emergence and obtaining stronger crop growth (Dugje et al., 2008). Also other advantageous effects of fertilizers include increasing soil nitrogen and other nutrients, replenishing the organic matter of the soil and increasing soil moisture holding capacity (Ikie et al., 2006).

‘Push–pull’ technology

The ‘push-pull’, as a tool in integrated pest management,

Table 1. Effect of soil fertility level on *Striga* growth and plant characters of 4 maize hybrids in Nigeria.

NPK % of recommended fertilizer	No of Striga plants/m of row[1]	No of Striga seed capsules /plant[1]	Maize plant height (cm) Res/Sus[1]	Grain Yield g/plant[1]
0	150	12	102/53	10
30	102	54	103/65	17
50	85	33	124/75	13
100	23	6	146/119	36

Source: Shank (2002).

first conceived by Pyke et al. (1987), and later formalized by Miller and Cowles (1990), involves use of behaviour-modifying stimuli to manipulate the distribution and abundance of a pest and/or beneficial insects for management of the pest (Cook et al., 2007). This technology was first developed to control stem borers but was later found to also suppress *Striga* weed in the field depending on which push component the main crop has been intercropped. In a 'push–pull' strategy, pests are repelled or deterred away from the target crop (push) by stimuli that mask host appearancy. The pests are simultaneously attracted (pull) to a trap crop where they are concentrated, leaving the target crop protected (Cook et al., 2007; Hassanali et al., 2008).

Desmodium is extremely effective in controlling *Striga*, resulting in significant yield increases in maize from 1 to 3.5 ton/ha per cropping season (Khan et al., 2008a) and improving farm productivity (Khan et. al. 2008b). In addition to benefits derived from increased availability of nitrogen, an allelopathic effect of the root exudates of desmodium is responsible for the dramatic reduction in *Striga* infestation (Khan et al., 2002). Secondary metabolites with *Striga* seed germination stimulatory and post-germination inhibitory activities are present in the root exudates of *D*. *uncinatum*, which directly interferes with parasitism (Khan et al., 2008c). This combination thus provides a novel means of *in situ* reduction of the *Striga* seed bank in the soil through efficient suicidal germination even in the presence of cereal hosts in the proximity (Khan et al., 2008c; Hooper et al., 2009). Other Desmodium spp. have also been evaluated and demonstrated similar effects on *Striga* (Khan et al., 2006a) and have been incorporated as intercrops in maize (Khan et al., 2007), sorghum (Khan et al., 2006b), millet (Midega et al., 2010) and rice (Pickett et al., 2010).

Desmodium also fixes atmospheric nitrogen (110 kg N/ha), adds organic matter to the soil, conserves soil moisture and enhances soil biodiversity, thereby improving soil health and fertility, which directly contribute to *Striga* control. Additionally, it provides ground cover and, together with surrounding Napier grass, protects the soil against erosion (Khan et al., 2006a).

It therefore improves agro-ecosystem sustainability, resilience, and has great potential to mitigate the effects of climate change. Both Desmodium and Napier grass provide valuable year-round quality animal forage whilst the sale of Desmodium seeds generates additional income for the farmers (Khan et al., 2008b). There are significantly higher returns to land and labor and overall gross benefits from this technology than from conventional farmer practices (Khan et al., 2008b) and other soil and *Striga* management practices (De Groote et al., 2009).

Desmodium has also been reported to have additional soil improvements such as; increasing of soil nitrogen, organic matter and conserving moisture (Khan et al. 2006). The 'push-pull', technology described involves intercropping maize with a repellent plant such as desmodium, *Desmodium uncinatum* Jacq., and planting an attractive trap plant such as *Napier grass*, *Pennisetum purpureum* Schumach, as a border crop around this intercrop. Gravid stem borer females are repelled from the main crop and are simultaneously attracted to the trap crop (Khan et al., 2000, 2001; Cook et al., 2007).

The technology, so far the most effective and indeed the only 'push–pull' strategy in practice by farmers (Cook et al., 2007; Hassanali et al., 2008), also enhances productivity of maize-based farming systems through *in situ* suppression and elimination of *Striga, S. hermonthica* (Khan et al., 2000, 2001, 2002). According to a study done by Khan (2010), push-pull technology helps controlling both *Striga* and stem borers with at least 2 tons per hectare higher grain yield. The technology is currently being disseminated among smallholder farmers in eastern Africa and adoption rates are rising.

Biological control method

The objective of weed biological control is not the eradication of weeds but the reduction and establishment of a weed population to a level below the economic threshold (Rajni and Mukerji, 2000). Means of biological control of weeds comprise herbivorous insects, microorganisms (especially fungi), and smother plants (Sauerborn and Kroschel, 1996). The method, involves importation, colonization, and establishment of exotic natural enemies, which include predators and parasitoids.

Efforts to manage weeds using biological control have been gaining momentum throughout the world, especially in the recent past (Delfosse, 2004). Biological control is considered as a potential cost-effective, safe and environmentally beneficial alternative mean of reducing weed populations in crops, forests or rangelands (Charudattan, 2001). Disadvantages of weed biological controls include it will usually require a long period (5 to 10) years of research and a high initial investment of capital and human resources (Culliney, 2005). Biological control is unattractive as a private entrepreneurial effort (Hill and Greathead, 2000; Coombs et al., 2004).

This is because the intensive use of chemical herbicides came under scrutiny due to several areas of concern, which include the development of herbicide resistant or tolerant weeds and environmental contaminations, comprehending effects on non-target organisms as well as the pollution of soil, underground water and food. Strong public criticism due to health concerns arose from such contaminations (Green et al., 1998). These limitations of chemical herbicides encouraged researchers to look for alternative systems of weed control.

Biological control using insects

The insects that attack *Striga* can be classified according to their damage as defoliators such as *Junonia spp*., gall forming as *Smicronyx spp*. (Coleoptera: Curculionidae) in India and Africa; shoot borers as *Apanteles sp*., miners as *Ophiomyia strigalis*, Spencer (Diptera: Agromyzidae) in East Africa; inflorescence feeders as *Stenoptilodes taprobanes* and fruit feeders as *Eulocastra spp*. (Lepidoptera: Noctuiidae) in India; (Kroschel et al., 1999).

In the 1990s, studies in Burkina Faso and Northern Ghana have been carried-out by Jost et al. (1996) and Traoré et al. (1996) to investigate the potential of the weevils *Smicronyx guineanus* and *Smicronyx umbrinus* and the butterfly *Junonia orithya* as biocontrol agents for *Striga*. As a result of Smicronyx infestation the *Striga* seed production was reduced by 17.4% on the average (Kroschel et al., 1999).

Kroschel et al. (1999) have been concluded that the use of herbivorous insects could play a role in an integrated control package, lowering the *Striga* population by reducing its reproduction capabilities and spread. However, the augmentation of native insect populations through inundative releases is not applicable in the third world, mainly due to the infeasibility of mass rearing.

Biological control using pathogens

Most organisms have natural enemies that balance their populations, avoiding excessive abundance (Templeton, 1982). Biological control of *S. hermonthica* using *Fusarium oxysporum* is considered as one of the novel management strategies (Sauerborn et al., 2007). Fungi are preferred to other microorganisms as bio-herbicides because they are usually host specific, highly aggressive, and easy to mass produce and are genetically diverse (Ciotola et al., 2000). Field and laboratory tests showed that *F. oxysporum* is highly effective in hindering germination, growth and development of Striga and thus may lead to reduction of Striga seed bank in the soil (Ciotola et al., 2003).

Extensive surveys in Burkina Faso, Mali and Niger also demonstrated the occurrence of highly pathogenic and *Striga* specific isolates of *F. oxysporum* (Ciotola et al., 2000). Among this isolate virulent isolate of *F. oxysproum* M12-4A provided more than 90% control of *Striga*, and a three-fold increase in sorghum biomass (Ciotola et al., 1996). The use of a myco-herbicide, that is *F. oxysporum* coated seeds and host plant resistance reportedly reduced *Striga* emergence by 95% and increased sorghum yield by 50% (Franke et al., 2006).

Recent findings indicated the effectiveness of integrated use of *F. oxysporum* compatible and *Striga* resistant sorghum genotypes to control *Striga* in Ethiopia (Rebeka et al., 2013). To realize the full potential of this approach it is important to recombine traits of Fusarium compatible and *Striga* resistant sorghum lines. This would allow continued selection of targeted progenies with combined resistance and Fusarium compatibility and for subsequent seed treatment of suitable hybrid(s) for direct use. Thus effective *Striga* control would be possible through synergistic effect of biocontrol and host resistance.

Recently, the combined application of two or more control measures has been promoted for effective *Striga* management. The use of bio-control agent such as virulent isolate of *F. oxysporum* f.sp. strigae as a component of integrated *Striga* management was identified to have several advantages (Ciotola et al., 2000; Fen et al., 2007). Marley et al. (2004) and Schaub et al. (2006) also found that the application of integrated *Striga* management package combining a mycoherbicide based on *F. oxysporum* isolate and host plant resistance has been demonstrated on farmers fields as effective *Striga* control approach. There is other agreed combined use of resistant varieties with the application of *Fusarium oxysporum* as pest granules or as a seed coating was reported to be effective to controlling *Striga* (Marley et al., 2004; Julien et al., 2009).

Various *Fusarium spp*. and *vesicular arbuscular mycorrhizal* (VAM) fungi have been found which can reduce *Striga* infestations significantly on sorghum and maize when used together with resistant host (Ciotola et al., 2000; Lendzemo et al., 2005; Franke et al., 2006). These control options when applied individually are not effective and sometimes affected by environmental conditions. Therefore the use of *F. oxysporum* in combination with other cost effective control methods may provide an effective and sustainable control option for subsistence farmers.

However, integrated *Striga* management approach relies on the use of resistant host genotypes and *Striga* pathogenic *F. oxysporum* application to control *S. hermonthica* emergence and growth lead to effective results (Hearne, 2009; Julien et al., 2009).

Chemical control method

Germination stimulants

Certain chemicals such as ethylene, ethephon, strigol and strigol analogues can induce germination of *Striga* seeds in the absence of a suitable host and therefore seed reserves in the soil (Esilaba and Ransom, 1997). In dicotyledonous plant species there is evidence that the production of strigolactone by the host plant could be reduced if sufficient minerals are available (Lopez-Raez et al. 2008).

Pre emergence herbicides

Technology currently being deployed as a complement to *Striga* resistance in maize involves use of herbicide as a seed coating. The parasite competes with its host for resources; changes host plant architecture and reduce the photosynthetic rate and the water use efficiency of the host (Watling and Press, 2001). This has led to the emergence of a new technology known as imazapyr-resistant maize (IRM) which has proven to be efficient for *Striga* control (Kanampiu et al., 2006; De Groote et al., 2006). The International Maize and Wheat Improvement Center (CIMMYT), Badische Anlin and Soda Fabrik (BASF), African Agricultural Technology Foundation (AATF) and other stakeholders have made efforts in bringing imazapyr-resistant maize (IRM) technology to farmers as assistance for *Striga* control.

Result of experiments also proved that herbicide seed treatment using imazapyr appears to be a promising approach for the control of *Striga* in maize or sorghum (Dembele et al., 2005). Ndung'u (2009) has also reported coating sorghum seed with herbicide reduced *Striga* infestation, *Striga* flowering and *Striga* seed set, and it is considered as the most effective approach as it does not affect sorghum biomass.

Research on-farm trials in Kenya and Tanzania indicate that seed dressing with Imazapyr and Pyrithiobac offers good *Striga* control and increased maize yields (Kanampiu et al., 2004). IR maize has been used in controlling *Striga* but is toxic to all other crops that do not have resistance to imazapyr herbicide, therefore not very suitable in mixed cropping systems. Many herbicides are useful in preventing the build-up of *Striga* seeds in the soil but may not prevent damage prior to their emergence (Kanampiu et al., 2003). The sustainability of many technologies will only be maintained when integrated with other technologies.

Post emergence herbicides

Herbicides tested for the selective control of *Striga* mostly acts through the foliage, although some have soil residual effects. Among the herbicides tested, 2, 4-D has been the most selective and is the cheapest. 2-methyl-4-chlorophenoxyacetic acid (MCPA), a compound closely related to 2, 4-D, has also been effective especially when mixed with bromoxynil (Ejeta et al., 1996). Post emergence application of 2,4-D (1 L product/ha), Glufosinate (2 L product/ha) and Oxyflourfen (1 L product/ha) was effective in preventing the top growth of *Striga.* Unfortunately, most of those products had narrow window of application and the only safe treatment for the crop was targeted spray of 2,4-D (Fasil, 2004). Babiker et al. (1996) reported that a combination of urea and dicamba effectively controlled *Striga* between 62-92% on sorghum, while chlorsulfuron in combination with dicamba controlled *Striga* as much as 77-100% on sorghum. However, results of the experiments showed that pre and post emergence herbicides do not prevent crop yield loss, because they cause their impact after *Striga* has already attached and damaged the host.

Research efforts on the identification of systemic herbicides, which could ideally translocate through the host crop to prevent initial stages of parasite development, were not successful. So Research efforts should therefore be directed towards identifying herbicides that persist in the soil, allowing the germination of *Striga* seeds but killing the seedlings before attachment to the host. Herbicides must also be compatible with the mixed cropping systems practiced by farmers and be profitable to use with low initial capital outlay.

Host plant resistance

Host plant resistance would probably be the most feasible and potential method for parasitic weed control. Using biotechnological approaches (including biochemistry, tissue culture, plant genetics and breeding, and molecular biology) significant progress has been made in developing screening methodologies and new laboratory assays, leading to the identification of better sources of parasitic weed host resistance (Ejeta et al., 2000; Haussmann et al., 2000; Omanya, 2001). It is potentially an acceptable *Striga* control option to resource-poor farmers (Gurney et al., 2003; Rich et al., 2004). However, reliance on host resistance alone is not ideal because so far complete resistance against *Striga* cannot be attained through breeding (Gurney et al., 2002), and usually the newly developed varieties may not fulfill farmers preference traits (Adugna, 2007).

Reports of genetic resistance to *Striga* have been documented in rice (Bennetzen et al., 2000; Gurney et al., 2006), sorghum (*Sorghum bicolor*) (Haussmann et

Table 2. Striga tolerant and resistant maize varieties developed and released in Nigeria.

Release name	Year of release	Hybrid/ OPV	Maturity range	Suitable agro-ecologies	Grain yield	Additional traits/remarks
Oba Super 7	2009	Hybrid	Medium-late	Moist savannas	High	Striga-resistant
Oba Super 9	2009	Hybrid	Medium-late	Moist savannas	High	Striga-resistant
Sammaz 15	2008	OPV	Medium-late	Moist savannas	High	Striga-tolerant with good nitrogen use efficiency
Sammaz 18	2009	OPV	Early	Guinea and Sudan Savanna	High	Striga-tolerant
Sammaz 19	2009	OPV	Medium-late	Moist savannas	High	Striga-tolerant
Sammaz 20	2009	OPV	Early	Guinea and Sudan Savanna	High	Striga-tolerant
Sammaz 26	2009	OPV	Medium-late	Moist savannas	High	Striga-tolerant
Sammaz 27	2009	OPV	Early	Guinea and Sudan Savanna	High	Striga-tolerant
Sammaz 28	2009	OPV	Extra-early	Guinea and Sudan Savanna	Medium	Striga-tolerant
Sammaz 29	2009	OPV	Extra-early	Guinea and Sudan Savanna	Medium	Striga-tolerant
Sammaz 32	2011	OPV	Extra-early	Guinea and Sudan Savanna	Medium	Striga-tolerant, drought escaping and QPM
Sammaz 33	2011	OPV	Extra-early	Guinea and Sudan Savanna	Medium	Striga-tolerant, drought escaping and QPM
Sammaz 34	2011	OPV	Early	Guinea and Sudan Savanna	High	Multiple cob bearing
Sammaz 35	2011	OPV	Early	Guinea and Sudan Savanna	High	Striga-tolerant
Sammaz 38	2011	OPV	Extra-early	Guinea and Sudan Savanna	Medium	Striga-resistant and QPM
Ifehybrid 5	2013	hybrid	Extra-early	Guinea and Sudan Savanna	High	Low soil nitrogen-tolerant, Striga-resistant, single-cross
Ifehybrid 6	2013	hybrid	Extra-early	Guinea and Sudan Savanna	High	Low soil nitrogen-tolerant, Striga-resistant, top-cross

Source: Prof. S. G. Ado shehuga@gmail.com, shehuado@hotmail.com

al., 2004; Mohamed et al., 2003; Rich et al., 2004), cowpea (Riopel and Timko, 1995) and maize (Adetimirin et al., 2000; Menkir, 2006). Identifying source germplasm with different resistance mechanisms can facilitate combining several resistance genes to obtain more durable and stable polygenic resistance to Striga in cereals (Ejeta et al., 2000; Menkir, 2006). Various molecular markers are also available for genetic analysis such as restriction fragment length polymorphisms (RFLPs) (Perumal et al., 2007), random amplification of polymorphic DNAs (RAPD) (Agrama and Tuinstra, 2003), amplified fragment length polymorphisms (AFLP) (Perumal et al., 2007), microsatellites or simple sequence repeats (SSRs) (Ganapathy et al., 2012) and single nucleotide polymorphisms (SNPs) (Arai-kichise et al., 2011). Various studies have reported combined use of phenotypic and molecular markers in genetic analyses of cereals such as ryegrass (Jianyang, 2005), rice (Ogunbayo et al., 2005), maize (Beyene et al., 2005; Wende et al., 2012), and sorghum (Agrama and Tuinstra, 2003; Anas and Tomohiko, 2004; Bucheyeki et al., 2009).

The use of resistant varieties has been highlighted as the most effective and environmentally sound method for the control of *Striga*. This has been demonstrated in multi-location field tests conducted in Ethiopia and Tanzania (Mbuwaga et al., 2007; Tesso et al., 2007). The International Institute for Tropical Agriculture (IITA) has released *Striga* resistant, drought-tolerant, and low soil nitrogen-tolerant extra-early maturing white maize varieties in Nigeria (Table 2).

There is also *Striga* resistant/tolerant maize hybrids and varieties released in West Africa are shown in Table 3.

Recognizing that improved cultivars of cowpea for West Africa incorporate resistance to both parasites (*S. gesnerioides* and *A. vogelii*), IITA developed cultivars with individual and dual parasite resistance. Several *Striga* and Alectra resistant varieties have been released in Africa. The variety, IT97K-499-35, has been adopted by

Table 3. Striga tolerant and resistant maize varieties developed and released in W. Africa.

Variety name	IITA designation	Types of cultivars	Country	Year of release	Adaptation zone
SAMMAZ11	Aer 97 TZL Comp 1-W	Striga tolerant late maturing OPV	Nigeria	2001	Moist savannas
SAMMAZ28	99TZEE-Y-STR	Extra-early Striga tolerant OPV	Nigeria	2001	Sudan Savannas
SAMMAZ29	2000SynEE-W-STR	Extra-early Striga tolerant OPV	Nigeria	2001	Sudan Savannas
SAMMAZ21	TZE Comp 5-W	Striga tolerant early maturing OPV	Nigeria	2001	Moist savannas and Sudan Savannas
SAMMAZ27	EV99DT-W-STR	Early drought and Striga tolerant OPV	Nigeria	2001	Moist savannas and Sudan Savannas
EV97DT-W- STR	TZE-W Pop DT STR C3	Early drought and Striga tolerant OPV	Benin Mali	2006 2008	Moist savannas and Sudan Savannas
SAMMAZ15	IWDC2SynF2	Striga tolerant medium maturing OPV	Nigeria	2008	Moist savannas
SAMMAZ16	TZLComp1SynW-1	Striga resistant late maturing OPV	Nigeria	2008	Moist savannas
Oba Super 7	H05-01STR	Stirga resistant hybrid	Nigeria	2009	Moist savannas
Oba Super 9	H05-02STR	Striga resistant hybrid	Nigeria	2009	Moist savannas

Source: Menkir, et.al. (2009). IITA.

approximately 600,000 farmers in northeastern Nigeria (Amaza et al., 2009). Improved varieties have better yields (1-2 ton/ha) than local farmers control (0.3-0.5 ton/ha). In rice, *Oryza glaberrima* lines 'ACC102196', 'Makassa', and 'IG 10', as well as *O. sativa* lines 'IR49255-BB-5-2' and IR47255-BB-5-4' showed partial resistance to *S. aspera* and *S. hermonthica* under field conditions in Cote d'Ivoire (Johnson *et al,* 2000).

More than 80 resistant sorghum lines have been selected by the International Center for Dryland Research (ICRSAT) in India. Recently, of these, some high yielding *Striga* resistant sorghum and millets varieties have been made by the Ethiopia Institute of Agriculture Research at Nazreth, and introduced and registered in the country Ethiopia (Table 4) (Adugna, 2007; Ejeta, 2007). These varieties when deployed along with moisture conservation practices and soil amendment inputs can dramatically reduce *Striga* infestation and increased sorghum yield by up to 400%. However, adoption of these varieties has been slow primarily due to the introduced germplasm do not fulfill farmers preferred traits (Adugna, 2007), and lack of effective seed production and delivery mechanism. Purdue University in USA also identified two sorghum varieties: P9401 and P9403 have been recommended for full commercial production. These varieties combine excellent grain quality and drought tolerance. They have been highly preferred by Ethiopian farmers. They were named Gubiye (P9401) and "Abshir (P9403) that are resistant or tolerant to *Striga*.

Hiriray, Higretay and Korokora are Ethiopian maize varieties that are resistant due to their early maturing characters, which is an escape mechanism against the infestation of *Striga* (Kidane et al., 2004). Promising results were also obtained in sorghum when both traits, *Striga* and drought resistance, were combined by classical breeding.

Basically the resistant varieties were low yielding and not desirable in other agronomic characteristics. However, integrating genetic resistance with other control measures is the smartest option possible both for effectiveness of control as well as for increasing durability of resistance genes (Ejeta, 2007).

Integrated Striga management

Striga has a high fecundity, it uses the host plants nutrients and the seed is asynchronous. These characteristics make the weed difficult to control (Andrianjaka et al., 2007). It is also difficult to control effectively because most of its damage to the host plant occurs underground before the parasitic plant emerges (Rich et al., 2004). The rate of infestation needs therefore to be managed through different control methods. Today there are several control options have been recommended to reduce *Striga* damage such as the use of resistant cultivars, crop rotation, intercropping with

Table 4. Introduced exotic sorghum and millets varieties released/registered in Ethiopia.

Crop	Variety name	Original name	Year of release/ registration	Source	Specific character
Sorghum	Dinkmash 86	ICSV 1	1986	ICRISAT	Early
Sorghum	Melkamash 79	Diallel Pop 7-682	1979	ICRISAT	
Sorghum	Kobomash 76	NES-830x705	1976	ICRISAT	
Sorghum	Seredo	Seredo	1986	ICRISAT	
Sorghum	76T1#14	76T1#14	1979	ICRISAT	
Sorghum	76T1#19	76T1#14	1976	ICRISAT	
Sorghum	76T1#23	76T1#23	1976	ICRISAT	Early
Sorghum	76T4#416	76T4#416	1976	ICRISAT	
Sorghum	Meko	M36121	2000	ICRISAT	Good food making quality
Sorghum	Teshale	3443-2-OP	2002	ICRISAT	
Sorghum	Gubiye	P9401	2000	Purdue University	Striga resistant
Sorghum	Abshir	P9403	2000	Purdue University	Striga resistant
Sorghum	Birhan	PSL5061	2002	Purdue University	Striga resistant
Sorghum	IS9302	IS9302	1986	ICRISAT	Adapted to mid altitude areas
Sorghum	IS9323	IS9323	1986	ICRISAT	
Sorghum	Red Swazi	Red Swazi	2007	ICRISAT	Early, malt sorghum variety
Sorghum	Macia	Macia	2007	ICRISAT	Malt sorghum variety
Sorghum	Yeju	ICSV 111Inc	2002	ICRISAT	
Sorghum	Hormat	ICSV 1112BF	2005	ICRISAT	Striga resistant
Finger millet	Tadesse	KNE#1098	1998	EARSAM	Good threshing quality and wide adaptation
Finger millet	Padet	KNE#409	1998	EARSAM	
Finger millet	Boneya	KNE#4011	2002	EARSAM	
Finger millet	Kola-1	ICMV 221	2007	ICRISAT	

Adugna, 2007.

pulse crops, late planting, deep planting, using trap crops, use of organic and inorganic fertilizers, herbicides, and biological control (Hearne, 2008). Although the level of *Striga* infestation and damage is increasing, farmers rarely adopt *Striga* control methods either due to limitations associated with the technology itself, access and costs of the technology or due to lack of information about available technology options (Oswald, 2005; Hearne, 2008). Furthermore, available options when applied individually are not effective and sometimes affected by environmental conditions.

Integration of weeding with high urea application, appropriate sowing date, and effective control of weeds which may serve as alternative hosts, will further enhance the long-term control of *Striga* (Fasil, 2002). Combined use of row planting, fertilizers and hand pulling (during flowering) registered 48% higher grain yield and over 50% reduction in *Striga* shoot counts compared to the farmer's practice at Adibakel (Table 5), in Tigray, Ethiopia (East Africa). However, from this result of research experiment showed that the best solution in the control of *Striga* is an integrated approach that includes a combination of methods that are affordable and acceptable by farmers.

Striga. According to the research findings, the integration of multiple control options is suggested as a better approach to combat *Striga* problem (Kuchinda et al., 2003; Schulz et al., 2003, Aliyu et al., 2004; Temam, 2006; Tesso et al., 2007). Schulz et al. (2003) and Hearne (2009) also proved that the best options for successful *Striga* control lies in an integrated *Striga* management (ISM) approach.

Table 5. Improved management practices on *Striga* infestation and sorghum yield (Adibakel)

Treatment	*Striga* count (Shoots/plot)	Grain yield (Kg/ha)	Biomass yield (Kg/ha)
Variety (V)			
Local check	262	307	4793
ICSV 1006	42	621	2440
ICSV 1007	166	549	2527
SRN 39	80	453	2840
Management (M)			
BC –F +HP	198	381	2767
BC +F +HP	193	532	3042
RP +F +HP	92	564	3483
RP –F +HP	141	393	2642
RP +F +2,4-D	73	541	3817
LSD (0.05) (V)	105	162	1149
LSD (0.05) (M)	117	181	NS
LSD (0.05) (V X M)	235	362	2569
CV (%)	80	35	39

BC, broadcasting; RP, row planting; HP, hand pulling; F – with (+) and without (-) fertilizer. Source: Fasil, 2002.

DISCUSSION

The seriousness of the *Striga* problem was repeatedly reaffirmed in many national and international workshop and research works. In many areas it is becoming steadily more serious, as in many Africa countries including other regions, there is considerable alarm resulting from the acute susceptibility of many of the new high-yielding sorghum and maize hybrids.

Available control measures were reviewed in detail. Most various control options (cultural, chemical, biological, and use of resistant varieties) are either impracticable for the majority of small farmers or too expensive or unavailable due to different reasons to reduce *Striga* damage. In the development of resistant varieties, there has been some notable progress as a result of IITA, CIMMYT, International Sorghum and Millets (INTSORMIL), ICRISAT's and other govenments and non governments efforts, but progress against the more virulent *S. hermonthica* has been less rapid. Variability in farming systems, literacy level, ecological peculiarities and farmers' resources will go a long way in the choice and use of method to apply. The important thing is to control this devastating parasitic weed, so as to enhance higher crop yield per hectare and to better the standard of living of poor resource farmers.

Considering the constraints to a successful control of parasitic weeds so far, it is well recognized that no single method of control can provide an effective and economically acceptable solution. Therefore, an integrated control approach is essential, ideal and useful to small-scale farmers, in order to achieve sustainable crop production. Therefore it needs to be adjusted to individual cropping systems, local needs and preferences may be helpful in adapting and optimizing control strategies to different agro-ecosystems.

RECOMMENDATIONS

Short term

Some of the points that should receive an immediate attention include:

i) Identify and mark the farms classified as to level of infestation and develop treatment plans according to cost and return potential
ii) Generate information from which farmers can make optimum decisions on choice of cereal species and variety, time and method of planting, mixed cropping, herbicide and hand pulling as relevant to the farming system.
iii) Use clean crop seeds to avoid *Striga.*
iv) Improve soil fertility by using fertilizers.
v) Crop rotation with non host crops or crops that induce suicidal germination.

Long term

To alleviate the alarming problem of *Striga* in the long-run emphasis should be placed on:

i) Research efforts should be focus on controlling the production of new *Striga* seeds and reducing the number of seeds in the soil.
ii) Demonstration of existing improved technologies that are effective and feasible for the small scale farmers.
iii) *Striga* control approaches, namely cultural, chemical, genetic, and biological options should be widely investigated and developed.
iv) Practices and measures should be easily affordable, economical, and practicable to poor farmers.
v) Finding suitable companion and trap crops that fit into

the farming systems of target communities.
vi) The use of trap crops as an intercrop with susceptible hosts to reduce the seed bank needs prolonged investigations.
vii) Effective preventive measures need to be taken through seed quarantine and *Striga* free equipment.
viii) Developing and use of resistant crop varieties.
ix) Demonstration and training should be strongly focus in integrated *Striga* control
x) Need to launch an action program for the control of *Striga*. This program should cover all aspects of the problem.

Conflict of Interests

The author(s) have not declared any conflict of interests.

ACKNOWLEDGMENTS

Great thanks to Fassil Reda (Ph.D.) Ethiopia Agricultural Research Institution agronomist for his critical reading and giving valuable comments of the manuscript. My appreciation is also to Diress Tsegaye (Ph.D.), Mekelle University lecturer in scientific research methods advising and sharing his technical knowledge. I would like to extend my special thanks to Zenebe Kibret (Tigray regional BoANR) and Tadesse W/ Berhan (Tigray regional Seed Production Enterprise) for their contribution in collecting materials.

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