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REVIEW **Open Access**

Tailoring IPM plans to fight a cloaked pest: helping smallholder farmers combat the sweetpotato weevil in sub-Saharan Africa

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Abstract

Africa accounts for a significant portion of the world's sweetpotato production where it is widely grown as a staple crop. In sub-Saharan Africa (SSA), sweetpotato serves as an important year-round source of calories and nutrition, a form of income for smallholder and pre-commercial farmers, and is increasingly used as silage for animal feed. However, yield per hectare is considerably lower in SSA than from other regions primarily due to sweetpotato weevils (SPW, *Cylas* spp., Coleoptera: Brentidae). Weevil feeding causes physical damage to the root and can induce chemical responses that give the storage root a bitter taste, both of which make them unmarketable. Commercial growers in many developed countries rely on frequent chemical treatments and strict quarantine regulations to control SPW, however, this approach is currently not practical for many areas of SSA. In this paper we, (1) outline factors that contribute to SPW infestation; (2) review available strategies and ongoing research for control of SPW, including chemical pesticides, biological control (macro-organismal as well as microbial control), cultural practices, selective breeding, and biotechnology; and (3) discuss the potential for implementing an integrated pest management (IPM) approach that leverages a combination of techniques. We rationalize that a multifaceted strategy for SPW control will improve both the quantity and quality of sweetpotato production in Africa.

Keywords Sweetpotato, Sweetpotato weevil, Cylas, Integrated pest management (IPM), Smallholder farmers, Host plant resistance, Cultural controls, Biological control, Microbial control

Background

Sweetpotato (*Ipomea batatas* L.) is widely grown and consumed in over 100 countries around the world due to its ability to produce under a wide range of abiotic conditions. Sweetpotato crops are valued for their drought-resistant characteristics and high productivity even in marginal soils (Rahaman et al. 2015). Sweetpotato is one of the top 10 most important food crops world-wide with over 7 million hectares planted every year; Africa accounts for more than half the area planted with an estimated 4.2 million hectares in 2021, however, due to poor yield they only account for 30% of the total global yield (FAOSTAT 2023).

Sweetpotato is particularly important for sub-Saharan African (SSA) nations which depend on it as a subsistence crop and potential source of income (Alam 2021; Nelles 2009). Sweetpotato, especially orange-fleshed varieties, can reduce malnutrition by providing high amounts of vitamin A, B, C and other essential nutrients (Alam et al. 2016; Low et al. 2015) and the crop is high in

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calories making it not only a good staple food, but also a valuable livestock feed source (Magoon et al. 1970). Although its protein content varies depending on variety and agronomic factors (Purcell et al. 1976; Walter et al. 1984), sweetpotato can be a good source of protein, making it extremely valuable for communities facing protein deficiencies. Furthermore, sweetpotato leaves can be harvested multiple times annually and offer high nutritional value similar to other leafy vegetables (Islam et al. 2003). In addition to the nutritional value, since 2010 Sweetpotato exports from Africa have significantly increased from about $10 M to over $71 M (FAOSTAT 2023).

In the USA, sweetpotato is generally propagated using *slips*, which are vines growing directly from sweetpotato roots which have been bedded for the purpose of producing material for propagation. Alternatively, in SSA, sweetpotato is generally propagated using *vines*, which come from a previous crop and can vary in age. Once planted, this fast-growing crop extends vines which cover the ground in only a few weeks, generally requiring low energy input and minimal care, aside from pest management (McEwan et al. 2015). There is great potential for improved yield in Africa, however. For example, over the last 50 years North America has experienced significant yield increases per hectare (8800 to 21,000 kg/ha) while yield of sweetpotato in Africa has realized only minimal improvement (5300 to 7000 kg/ha) (FAOSTAT 2023). Insect pressure in Africa is likely among the many variables responsible for poor crop production, but protecting sweetpotato yield from pests is critical for promoting health and economic growth in SSA.

Sweetpotato weevils (SPW) are the most important insect pests of sweetpotato and can be found in various regions globally (Okonya et al. 2016; CABI 2020). For most of the world the sweetpotato weevil species *Cylas formicarius* is considered the most problematic, however in SSA two other species are primarily responsible for considerable losses, *C. brunneus* and *C. puncticollis* (Grüneberg et al. 2015). There are several insects which feed on sweetpotato, however, generally only those that damage the root or transmit disease are considered economically important. Among those, SPW are unique in that they complete their life cycle within the root or stem. This cryptic attribute also makes SPW difficult to manage as damage is not observed until harvest, and the effect it has on the sweetpotato root quality significantly reduces marketability (Fite et al. 2014; Okonya et al. 2016; vanVugt and Franke 2018). In some areas, if SPW populations are left uncontrolled, growers have reported up to 100% infestation rates and varying, but significant loss due to weevil damage (Tanzubil 2015). Furthermore, it has been reported that sweetpotato plants respond to SPW-feeding damage by producing terpenoid molecules which render the roots bitter and unpalatable (Ray et al. 2010; Uritani et al. 1975).

In this review we discuss the factors that lead to SPW infestation, briefly summarize the current state of knowledge and research regarding SPW control and highlight methods and opportunities for integrated pest management (IPM) of SPW, with particular focus on sub-Saharan Africa. Additionally, we comment on future research and development opportunities. Our review suggests that no single tool or practice or IPM strategy used in one region will be adequate for SPW control in a differing region; and therefore, an IPM approach must be tailored for a particular area and circumstance to be successful.

Sweetpotato weevil biology and its associated damage

The primary pests, *Cylas brunneus*, *C. formicarius*, and *C. puncticollis* (Coleoptera: Brentidae) are similar in their life history and feeding injury to sweetpotato plants and storage roots (Chalfant et al. 1990; Ames et al. 1997; Smit and van Huis 1998; Korada et al. 2010; Hue and Low 2015; Johnson and Gurr 2016; Kyereko et al. 2019). Each of these species are commonly referred to as sweetpotato weevils and characteristically have blunt snouts approximately as long as their thorax. *Cylas puncticollis* is the largest of the three SPW pests as an adult and is uniformly black, whereas *C. formicarius* has a reddish-brown head and thorax with a bluish-black abdomen. The color of *C. brunneus* adults varies but includes some reddish-brown tint over the thorax; it is the smallest of the *Cylas* spp. (Musana et al. 2016). Other weevil pests of sweetpotato exist, but the three described herein would be the most significant species for one or more of the regions emphasized in this review. *Cylas formicarius* is found worldwide in tropical and subtropical regions and is the only sweetpotato weevil pest species in the USA. *Cylas puncticollis* and *C. brunneus* are only found in Africa. In this review, we will denote any of the described species simply as sweetpotato weevil or SPW, unless a particular aspect pertains to only a certain species.

Sweetpotato weevils have a narrow host range, predominantly favoring sweetpotato crops (*I. batatas*); however, they have also been observed on other plants within the Convolvulaceae family including those in the genus *Ipomoea* (Reddy and Chi 2015; Sutherland 1986), which includes plants commonly known as morning glory, water spinach, bindweed, moonflower, and many others. Secondary host plants include, but are not limited to: *Calystegia hederaca (Japanese false bindweed), Cuscuta* spp. (dodder), *Dichondra carolinensis* Michx (Carolina ponysfoot), *I. triloba (three-lobe morning glory), I. pes-caprae (beach morning glory)*, and *I. indica (ocean-blue morning glory)* (Komi 2000; Reddy and Chi 2015;

Cockerham 1954). Many of these species grow in the wild or as weeds and provide a refuge for SPW outside of the cropping season.

The life cycle of all the *Cylas* sweetpotato weevil species is similar and has been previously reviewed by several authors (Chalfant et al. 1990; Ames et al. 1997; Korada et al. 2010; Hue and Low 2015; Johnson and Gurr 2016; Kyereko et al. 2019). In brief, all stages are routinely associated with sweetpotato (Fig. 1) or other *Ipomoea* plants. Adults can be found feeding on the underside of leaves, vines, and exposed roots (Nottingham et al. 1988; Chalfant et al. 1990). Mated females oviposit first by creating a small hole, then lay a single whitish egg within the feeding hole on storage roots or vines, depending on the species. Oviposition sites on roots can be distinguished from feeding damage by the presence of a fecal plug. Weevils cannot dig; thus females must access storage roots through soil cracks (Ames et al. 1997). After approximately 8 days, the eggs hatch into larvae and begin burrowing further into the plant, leaving frass in their path and exposing the crop to fungal infections that cause rotting of the sweetpotato roots (Onwueme and Charles 1994). The larvae are legless and cause the majority of damage to the plant by tunneling through sweetpotato vines and storage roots. Larval development and pupation occur entirely within the plant. The developmental period, or the time it takes for an insect to mature from egg to adult, is different for each species, being 25–31 days for *C. formicarius*, 16–32 days for *C. puncticollis*, and 32–41 days for *C. brunneus* (Smit and Van Huis

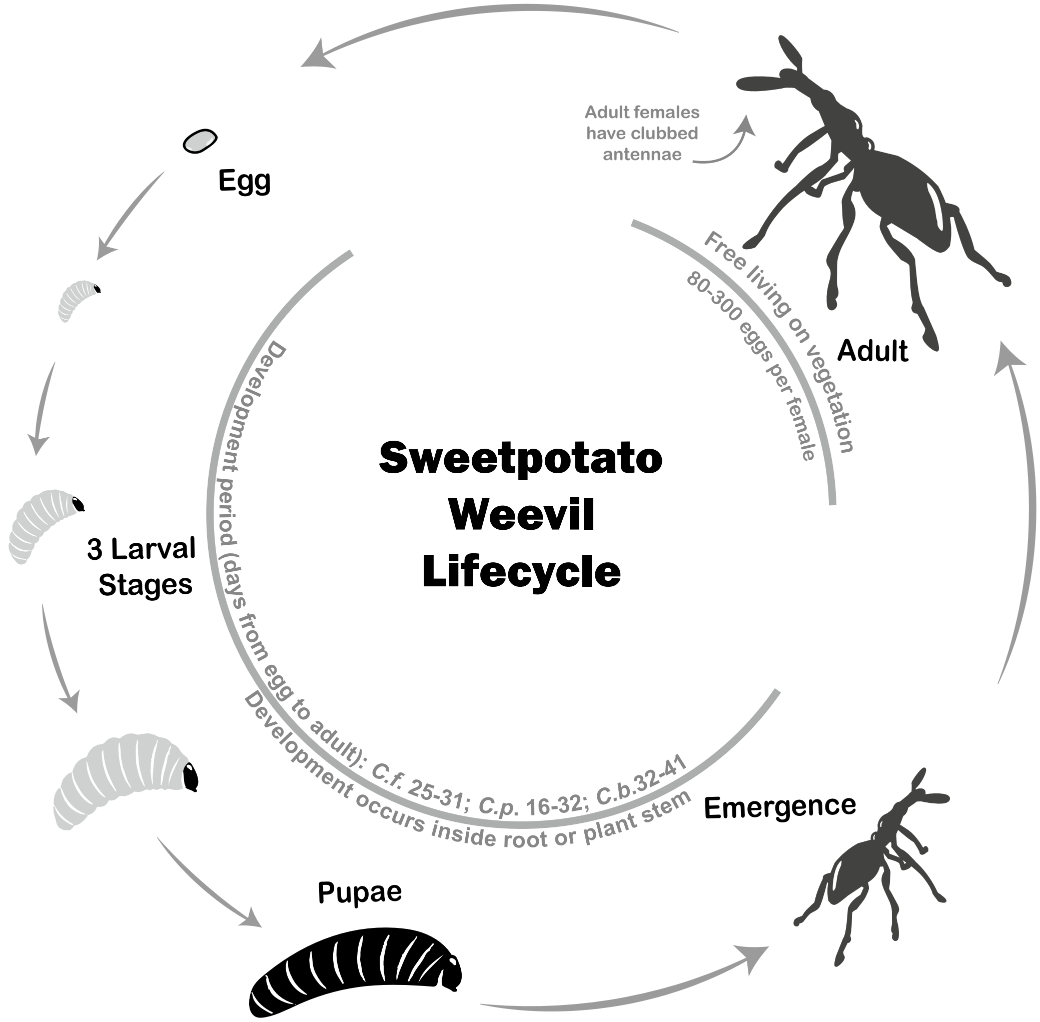


Fig. 1 Life cycle of the sweetpotato weevil and the associated location within or on the host plant for the various life stages. The life cycle depicted is representative of that typically observed for *C. formicarius (C.f.)*, *C. brunneus (C.b)*, and *C. puncticollis (C.p)*, and is not intended to be specific for one of the 3 spp

1998). Following pupation and after eclosion, adults can remain in the root for a few days prior to emergence. This cryptic lifestyle makes it difficult to observe or assess the presence of SPW without destroying the plant. The average time of development from egg to adult among the major pests under suitable environmental conditions is 35 days and female egg production ranges from 80 to 250 eggs over its adult lifetime of approximately 4 months (Stathers et al. 2013; Sherman and Tamashiro 1954).

The factors that contribute to SPW infestation are varied, and encompass aspects of pest biology, agronomic practices, pest reservoir population, planting material, economics, and pest awareness. These principal factors contributing to SPW infestation are summarized in Table 1.

Integrated pest management and SPW control

Integrated pest management (IPM) is a decision making approach to manage pests using a set of tools and tactics which limit impacts on growers, the environment, and society. This is done through the integration of various control measures in an overall pest strategy or plan. The ins and outs of what has been considered as included in IPM or its main emphasis have varied amongst adopters in developed and developing countries and over time (Ehler 2006; Pretty and Pervez Bharucha 2015; Deguine et al. 2021; Srinivasan et al. 2022), leading some to consider that even in developed countries, the original vision of IPM has not been achieved (Ehler and Bottrell 2000; Deguine et al. 2021). The latter opinion recognizes the importance of the "integrated" aspect of IPM which can at times be lacking.

Regardless of all that is included in one's concept of IPM, the IPM plan takes into account practices required to maintain crop production while minimizing risk to human health (FAO 2012). While classic IPM plans focus heavily on economic and ecological inputs (Stern et al. 1959; Kogan 1998), some have suggested that IPM would also benefit from "modernization" by expanding its considerations of management, business, and sustainability aspects combined with social acceptability (Dara 2019). For example, the advocated modernization would encompass achieving consumer confidence in the production system(s), and also take into account such areas as global food security issues (Dara 2019).

The control measures chosen as part of an IPM approach can consist of host plant resistance, cultural, biological (including microbial applications), chemical, or biotechnological controls. Also, these various options can be implemented spatially or temporally as needed for the specific plan. In practice, IPM plans are often fluid and require reconsideration and strategizing as both local and larger scale concerns may arise and as tools, technologies, control methods or even registration status of a control agent may change. For example, the USDA (2018) has a "roadmap" for IPM adoption, but it has built-in expectations of the evolving nature of IPM. Concerning insect pests, while IPM and Insect Resistance Management (IRM) are distinct components of modern agriculture and have different goals in mind, an overarching IPM plan can be complementary with IRM. For example, if chemical, or biological-based insecticide choices (that may be driven as part of IRM) are considered in terms of the potential impact these control agents may have on other essential components of IPM (e.g., preservation of natural enemies), then the differing goals can be satisfied.

In the sections which follow, we will consider numerous IPM control tactics which have been implemented or which have potential for implementation or enhancement to impact problems associated with SPW pest populations (see also Fig. 2). These are described as "current and potential" because what is current in one region may (or may not) be current or have potential for adoption in another region. In addition, while some practices are currently in place in a certain region, even those often have potential for broader adoption or methodological enhancement.

Embracing the concept of IPM, we consider de facto that a variety of control practices must be considered. And amongst those practices that are available/in place,

Table 1 Major factors contributing to SPW infestation

Pest biology	Cryptic life cycle which renders subterranean stages undisclosed or inaccessible
Agronomic practices	Pest build-up due to in-field debris of infested sweetpotato; plant stressors due to inadequate water, leading to cracks and pest access to roots; inadequate soil nutrients, or competition with weeds
Pest reservoir population	Ubiquitous pest presence in diverse set of alternative hosts, adjacent to fields locally and area-wide, which support a continual influx of the pest population
Planting material	Lack of certified clean planting material, or uniform access to clean planting material, insufficient and informal distribution channels for clean planting materials
Economics	Inability to invest in or access available control options
Pest awareness	Inadequate knowledge of the pest or the capacity to monitor its presence in the field

they could still benefit from further research improvements (e.g., to use innovative techniques that may become available, or to help combat insect resistance issues to a practice that may develop over time). While not ordered in any particular hierarchy, the first two practices that will be presented in our review (host plant resistance and cultural controls) have a long and well-established history and are clearly of benefit. If an existing option for a given region, these control tactics also come with the advantage of ease of implementation for the smallholder farmer situation that describes much of SSA with regard to sweetpotato production.

Further on in this review, we will pose the question of whether the IPM strategies for SPW in SSA should mimic that of other regions, contrasting the practices for SPW control in the US versus SSA with the aid of a summary figure (Fig. 2). We have also taken the view that several of the control practices are foundational to successful IPM for SPW, irrespective of the region where the pest may be found, and thus capture this view within the summary figure. We will then present a series of recommendations for future sweetpotato weevil IPM in SSA.

Current and potential control tactics

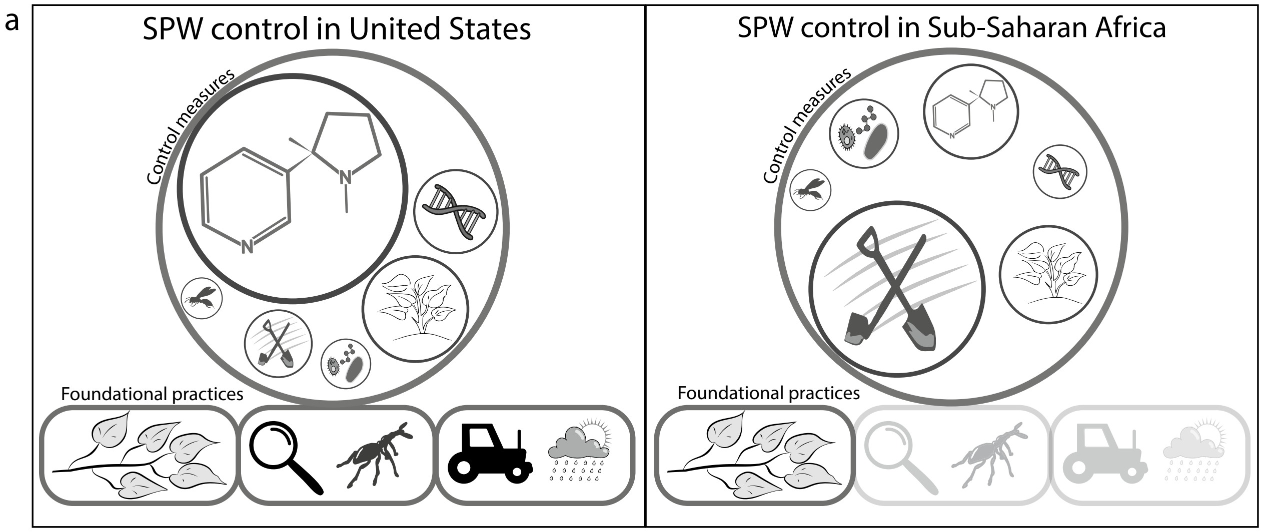
Host plant resistance

Host plant resistance is the use of plant varieties or cultivars which differ in their susceptibility to pests (Stout 2014). Breeding for resistance to pests is an ongoing area of improvement in sweetpotato. While much of the emphasis has been towards selection of resistance to diseases and drought (Low et al. 2020; Mwanga et al. 2017), breeding for resistance to SPW has not been ignored. Three general selection strategies for SPW resistance have been described in the context of efforts for SSA: (1) varieties that would "escape" SPW via deeper root growth habit, or at least minimizing root growth that would crack the soil surface, (2) varieties that would mature earlier (to avoid increased pest damage), and (3) varieties that would exhibit a "non-preference" in terms of the SPW affinity for the selected variety as compared to other varieties (Stathers et al. 2003). Such breeding efforts have been a bit discouraging, as heavy weevil infestation persists (in particular when pest pressure is high) following many years of attempts with available germplasm (Talekar 1987a; Stathers et al. 2003). In part, host plant resistance for SSA may have been difficult to achieve due to breeding tactics that lacked an appreciation of how best to approach the challenge of sweet potato genetic variation. For sweetpotato, there can be superior parental genotypes identified that favor general combining ability, but there are also specific combining abilities which can be identified when tracking a particular trait (such as SPW resistance) for crop improvement (Mugisa et al. 2022). While historical trends have led some to regard SPW resistance as less likely to be achieved in SSA, some recent efforts have shown promise (Kagimbo et al. 2020; Joseph et al. 2022; Mugisa et al. 2022). In at least one of these recent SSA efforts (Kagimbo et al. 2020), there is indication that the germplasm resistance may be based on a mechanism in common with that found from selection efforts that were successful in the USA. For example, in Tanzania (Kagimbo et al. 2020) genotypes found to be resistant were consistent with selection based on significant varietal differences in phytochemicals (including hydroxycinnamic acid esters), and a decrease in the presence of plant chemicals that are known to act as SPW oviposition stimulants (Stevenson et al. 2009; Anyanga et al. 2013). Other recent work (Anyanga et al. 2017), corroborated the presence of phytochemicals as associated with SPW resistance for a previously-identified local landrace variety, New Kawogo in Uganda (Muyinza et al. 2012; Anyanga et al. 2013). It was demonstrated that this variety can segregate in an F1 population into progenies, some containing higher levels of the hydroxycinnamic acid esters, signifying breeding for resistance can be achieved through population improvement (i.e., using the hydroxycinnamic acid ester content as a decision tool for sweetpotato breeding programs) (Anyanga et al. 2017).

Breeding of sweetpotato for given traits has, however, been described as a difficult practice in general, and in particular for SSA. The highly heterozygous hexaploid genome of *I. batatas* complicates genetic studies and limits improvement of sweetpotato through conventional breeding; this characteristic, coupled with pollen sterility, cross incompatibility, poor seed germination, and the routine of a largely clonal propagation strategy (Mwanga et al. 2017) continues to be a challenge for breeding success. This latter point implies that unless a step for the

(See figure on next page.)

Fig. 2 Implementation and availability of management practices for SPW control in different regions. **a** Pictorial comparison of SPW control measures in the USA and SSA. The size of the circle around each respective control measure approximates its perceived level of current implementation. In addition, the gray shading for certain foundational practices indicates it is in need of strengthening or increased implementation. **b** Detailed assessment of SPW control measures in the USA versus SSA. The assessment of implementation is approximated with a High, Medium, or Low ranking (e.g. high = routinely implemented or in place as well-established in the region, low = not widely implemented or poorly established), with comments on perceived availability of the respective practice



b

Control measures	United States	Sub-Saharan Africa
Host plant resistance	High Over 80 years of research with resistant varieties in the market. Current breeding programs generally target size and shape.	Medium Some breeding programs focused on varieties that are weevil-resistant.
Cultural control	Medium Some crop rotation, removal of plant material after harvest and use of border crops.	High Widely used by small-holder farmers. Ridging, some intercropping, and in-ground storage.
Macro-organismal control	Low Not actively deployed. Likely some natural control takes place. May be limited due to chemical applications.	Low Not actively deployed. Likely some natural control takes place. Little research available.
Microbial control	Low Few products on the market. Rarely used for SPW, likely due to need for high levels of control.	Low Despite promising research efforts, few products are on market. Currently cost prohibitive for small-holder farmers.
Chemical control	High Primary approach, applied regularly. Also used for post harvest prevention.	Low Some general insecticide products available not specifically labeled for SPW. Cost prohibitive for small-holder farmers.
Biotechnology	Low No transgenic sweetpotato, RNAi, or sterile male approaches available.	Low No transgenic sweetpotato, RNAi, or sterile male approaches available. Future oppurtuities face difficult regulatory landscape.
Foundational practices		
Clean planting material	High Newly produced slips used for planting. Certified clean varieties.	Medium Vines used for planting material. Distribution of clean vines used only in some areas.
Pest knowledge and monitoring	High Pheromone traps for monitoring used regularly. Quarantine mandates in place. Easy access to pest expertise.	Low No commercial pheromone traps available for monitoring. No regulation to prevent spread. Limited access to expertise.
Agronomic practices	High Uniform planting, harvest and storage. Tools for monitoring abiotic conditions, adequate H_2O, and plant nutrition.	Low Generally hand planted and maintained, in-ground storage. No monitoring of abiotic conditions. Zero inputs.

Fig. 2 (See legend on previous page.)

generation of true seed is involved, recombination and selection across new genotypes can not advance. The generation of true seed (seeds from cross-pollinated flowers) is required for breeding efforts, but since the use of clonally-derived material is so widespread, it has been proposed that a twofold breeding effort would be successful (Mwanga et al. 2017). This strategy consists of variety development (assisted by clonal propagation, and use of multiple location testing) and sweetpotato stock population improvement (following crosses and seed generation (Mwanga et al. 2017; Gallais 2003). A further difficulty basic to sweetpotato breeding exists in the dearth of molecular genetic tools to support breeding strategies (Mwanga et al. 2017), however, this area, too, has indicated that some improvement is on the horizon. For example, simple sequence repeat (SSR) markers associated with inheritance of hydroxycinnamic acid esters have been identified and the markers are being used for characterization and identification of parental genotypes toward improving SPW resistance (Yada et al. 2017).

Cultural controls

Cultural control is the deliberate alteration of the production system to reduce pest populations or avoid pest injury to crops by employing techniques to make the cropping environment less favorable for pest dispersal and survival. Several studies which have shown that implementation of cultural controls can significantly reduce crop damage by SPW will be considered in this section. Many of these cultural control practices focus on taking advantage of insect behavior to either protect plants or reduce insect populations. In SSA, various cultural practices are well established and should continue to be used; however, they will become most effective when coupled with other control measures. The following paragraphs in this section summarize cultural control practices which encompass field maintenance approaches as well as land stewardship practices; these are not presented in any intended hierarchy for their implementation.

Ridging

There are several tactical approaches that a grower can deploy to mitigate the abundance of SPW in a particular field or the impact of SPW on the crop. To reduce exposure of the storage roots, re-ridging, also known as earthing-up or hilling-up, is the practice of adding soil to sweetpotato mounds throughout the season to cover cracks that result from dry ground and bulking of the roots. This practice has been shown as effective in several studies (Kyereko et al. 2019; Beyene 2015). *Cylas* spp. prefer to deposit eggs in sweetpotato roots, however SPW do not burrow or dig through soil to access the roots, but instead rely on accessing roots via cracks formed in mounds. Such cracks develop as the sweetpotato bulks up and/or as soil dries, therefore covering those cracks can prevent SPW from accessing the root for oviposition. This cultural control tactic works especially well for *C. formicarius* species, which will only deposit eggs in the root; however, *C. puncticollis* and *C. brunneus* deposit eggs in the stem at the base of plants (pers. observ.) which may circumvent the re-ridging efforts.

Mulching

Another somewhat similar approach involves the use of mulching around the sweetpotato plants. This can provide components that assist with plant nutrition, reduce soil erosion, and help with irrigation efforts, as well as the deterring of pests by manipulating olfactory perception (Mansaray et al. 2015; Rehman et al. 2019), ultimately resulting in increased yield of sweetpotato storage roots and a decreased percentage of infested roots. For example, a field study examining control of SPW in Australia (Rehman et al. 2019) found mulching could result in a decreased movement of the SPW toward the protected sweetpotato plants and a concomitant decreased damage to the storage roots when the SPW were released from a nearby location. The mulching materials which seemed most effective in their study were cypress, eucalyptus, lucerne and basil (Rehman et al. 2019). Although this type of protective effect is believed to be attributed to plant volatiles that the mulch could provide, it has been rightly pointed out that the addition of mulch is a somewhat complex cultural control practice as it also can decrease the degree of soil cracking (Talekar 1987b) (by conserving soil moisture), provide a physical barrier, and ameliorate the habitat for desired natural enemies (Mansaray et al. 2015). The use of mulching for sweetpotato cultivation has not been adopted as a routine practice in SSA (personal observation).

Field sanitation

Sanitation, or the removal of SPW infested and/or discarded plant material from the field, is another cultural control practice which is very important to prevent SPW population build-up (Chittenden 1919). Any residual portion of previously-infested sweetpotato plants, be it from storage roots in the ground, discarded or volunteer vines in a portion of the field, or nearby infested “seed beds” intended for future vegetative propagation can all easily serve as an infestation epicenter for a subsequently planted sweetpotato crop. One interesting exception to this general guidance regarding the need for sanitation is a compromise that exists in the case of SSA whereby smallholder farmers routinely follow the practice of in-ground root storage in the sweetpotato field, gradually harvesting the storage roots as needed for consumption. It has been observed that this practice may be an acceptable compromise, not actually contributing to an increase in SPW presence in those storage roots since the farmers likely harvest roots that are exposed or closest to the surface first, and may even fill in digging sites with soil after uncovering those lower storage roots that remain (Smit 1997a). However, if sweetpotato cultivation were to grow beyond supporting subsistence and local population needs, this in-ground storage practice would likely be incompatible with the higher standard required for sweetpotato as a commodity in the marketplace.

Intercropping and barrier planting

Several cultural control approaches focus more on strategic land use or following stewardship of the planting regimes to reduce the level of SPW attack. One such approach which has been tested in other regions (e.g., Indonesia, India) involves intercropping with non-host plants or planting barrier plants which can reduce pest population build up (Yaku 1992; Nedunchezhiyan et al. 2010). This practice has been suggested as potentially valuable against SPW, due to the limited flying capabilities of SPW. It has been noted, however, that trade-offs for individual crop productivity may occur (Dada et al. 2020), which was the case when sweetpotato was intercropped with maize (Yaku 1992; Nedunchezhiyan et al. 2010), but less so when intercropped with the legume, red gram (Nedunchezhiyan et al. 2010). Importantly, any trade-off of individual crop productivity may be acceptable as part of a strategy to achieve an overall increase in the relative total yield per land area used for the intercropped scenario (Yaku 1992). This may require some fine-tuning in the choice of the intercropped plantings, however, such as intercropping of an early-maturing maize variety along with a shade-tolerant sweetpotato variety (Amede and Nigatu 2001). As far as the measured protective effect against incidence of SPW, the data indicate that fewer SPW may be found from sweetpotato in the intercropped scenario(s), along with a decreased percent of damaged tubers, with the effect being modest at a few percent difference (Nedunchezhiyan et al. 2010) to significant (e.g., 16-fold fewer SPW/kg storage roots and 19% fewer damaged storage roots) (Yaku 1992). Similar to what was noted previously regarding the cultural practice of using mulch, there may be an additional benefit of intercropping which comes by way of providing an increased presence of natural enemies of SPW (Yaku 1992). Somewhat related to the intercropping strategy of reducing SPW access to the sweetpotato, is the practice of using barrier plants around the sweetpotato crop. Barrier plantings of chives and perhaps basil have indicated a numerically lower incidence of SPW and feeding holes in storage roots as compared to control sweetpotato plantings that lacked the barrier crop (Dada et al. 2020). This does not appear to be a widely-used practice. Similar to the observation re: mulching above, the control practice of intercropping may be incompatible with large scale commercial-type sweetpotato production.

An interesting, more complex form of intercropping where highly susceptible varieties are used sacrificially to pull pests away from less susceptible varieties (also called 'intracropping') has been tried for sweetpotato (Ichinose et al. 2019). Varieties of sweetpotato that differ in SPW preference (see host plant resistance control tactic section) were tested in an experimental design with the two varieties in separate, but adjacent plots and resulted in one variety preferentially attracting weevils away from the other less preferred variety (Ichinose et al. 2019).

Crop rotation

The cultural control practice of crop rotation, well established as advisable for many other cropping systems (Padgitt et al. 2000; Mohler and Johnson 2009) has also been recommended for consideration with sweetpotato (Talekar 1983). In the context of SSA, studies have shown that *C. puncticollis* can survive up to a maximum of approximately 10 months (Okonya et al. 2016), thus, the prevention of SPW population build up through the use of crop rotation would seem to have some potential. In the case of sweetpotato, crop rotation with millet, cowpea, cassava, sorghum, maize, beans, rice, or fallow plantings have been tried with varying degrees of success (Ebregt et al. 2004; Talekar 1983; Powell et al. 2001). Talekar (1983) found that crop rotation with rice could be effective if used in an isolated situation, but easily overwhelmed by the influx of SPW that may exist in the vicinity of the plot area (e.g., from nearby fields under continuous sweetpotato cultivation).

Removal of alternative host plants

Removal of alternative host plants of the SPW has also been investigated as a cultural control tactic. Multiple alternative host plants for SPW have been identified within the Convolvulaceae (bindweed) family and the Ipomoea genus itself is quite large with hundreds of wild spp. (Mwanga et al. 2017); (Note: refer to the section 'sweetpotato weevil biology and its associated damage' for some further details and examples). The removal of alternative host plants seems most effective as a practice when implemented in isolated areas (Komi 2000) (i.e., those areas separated from large populations of SPW which could enter from adjacent fields) or in combination with other practices such as crop rotation (Talekar 1983).

Quarantine

Use of quarantine is a stewardship-type cultural approach which limits distribution of products outside of weevil-infested areas until SPW can be controlled. These measures have proven effective in developed countries, significantly reducing the spread of SPW. For quarantine to be effective, multiple measures must be enacted, which if followed may significantly reduce the spread of SPW. These measures may include: (i) restrictions on movement of sweetpotato plants, tubers, vines and any other material that may harbor SPW—processed products from sweetpotato may be exempt; (ii) inspections and certification of any material that is moved between quarantine and non-quarantined areas; (iii) treatment and disinfections of material; (iv) education to promote awareness and vigilance; and (v) research and monitoring to ensure regulations are followed and are effective. Generally, imposing a quarantine requires a regulatory agency to implement, monitor and enforce participation. In SSA many countries have phyto-sanitation agencies that inspect planting material or produce at country borders; these agents may reject the movement of some SPW infested material, although the cryptic nature of SPW makes detection difficult during border inspections (personal observation). We are unaware of any intra-national quarantine measures in relation to SPW in sub-Saharan Africa at this time. In SSA, sweetpotato is primarily produced by many small-holder farmers which may sell to local markets or larger distributors. This agricultural production system makes the implementation of state-regulated stewardship approaches difficult to enforce. A conscientious grower could self-impose some restrictions to limit spread of SPW to neighbors; however, this would be less impactful than a regional quarantine.

Clean planting materials

Use of clean planting materials is an especially important cultural control practice (Chittenden 1919; Sherman and Tamashiro 1954; Hundayehu et al. 2022). It has long been noted that since the SPW is not a prolific flier, its distribution spreads mostly based on infested storage roots or propagation material (Chittenden 1919). Planting sweetpotato vines that are uninfested with SPW reduces SPW damage through delaying the field infestation build up (Sherman and Tamashiro 1954). We consider this control practice so essential as to categorize it as a 'foundational practice' recommended to be in place (see Fig. 2). An innovative approach to making clean planting material available for the smallholder farmer named the Triple S method ("Storage in Sand and Sprouting") has been tested and validated (Hundayehu et al. 2022) and is proposed to be particularly helpful for dry areas of Africa. This innovation was fueled by observation that even with a distribution program in place for clean planting material, in the driest areas the material is easily lost within a few seasons (Hundayehu et al. 2022), hence, some alternative was needed. The Triple S method attempts to overcome the distribution limitations by providing conditions whereby the locally stored roots sprout slowly (in a container, covered by layers of sand for storage), survive an ensuing dry period, and are subject to minimal loss due to rotting or weight reduction (Namanda et al. 2013; Stathers et al. 2017).

Early harvesting

Distinct from use of early-maturing varieties (described previously in the section on host plant resistance), early harvesting of sweetpotato storage roots is a cultural control practice which has been suggested as a method to reduce SPW damage. Early harvesting is based on a tactic of removal of the crop prior to a large population build-up of SPW having taken place (Smit 1997b). If this practice is followed however, it does come with a few major trade-offs such as less crop yield (due to a shorter period of crop growth), and an excess of harvested material available at one time in the locality of the smallholder farmers adopting this method (Smit 1997b). This proposed practice is not routinely followed in SSA due to the lack of appropriate storage facilities, coupled with a preference for in-ground storage of the roots (personal observation).

Biological control

Various biological control measures which use natural enemies that target SPW eggs, larvae or adults have been explored. These practices often originated following observations of a naturally occurring control organism during the study of SPW biology or while noting the pest presence in the field. Preservation of a habitat for a natural enemy population that is already present can be an option to enhance biological control organisms that are naturally occurring as well. The use of biological control measures has not been widely implemented, and most opportunities are largely in a research phase of consideration or documentation. In this review we distinguish between two types of biological control (see Fig. 2), viz. macro-organismal control (nematodes, parasitoids and other predators) and microbial control (bacteria, virus, fungi, and other microbial agents). This distinction is helpful as the development, production, distribution and application of macro-organismal control agents are generally different from microbial control agents; this differentiation has an impact on how readily the control agents can be incorporated into a IPM program for SPW control.

Entomopathogenic nematodes

The use of entomopathogenic nematodes has been investigated as a tool to control sweetpotato weevils. Although some studies in the lab or using small scale plantings have demonstrated mortality of SPW by the addition of entomopathogenic nematodes (Mannion and Jansson 1992; Ekanayakei et al. 2001; Myers et al. 2020), schemes for how this approach could be reproducibly and reliably implemented as a field control measure are still forthcoming. Entomopathogenic nematodes have been used successfully for many other pest problems in agriculture (Georgis et al. 2006; Vega and Kaya 2012), and it is intriguing to consider their use for sweetpotato weevil, given the subterranean stages of the pest. However, it seems that much more research (e.g., development of a consistently effective nematode solution and its manufacturing process, as well as making it cost-effective) will be necessary prior to this approach making a major impact in sweetpotato weevil control.

Parasitoids

The impact of parasitoids is another biological control option which is considered in some IPM strategies. For SPW, although examples of parasitism (Cockerham 1944; Maeto and Uesato 2007) have been observed in field settings (or from material brought back into a laboratory for investigation), it is far less clear that this tactic will be available for strategic use in the future. Fifteen different wasp species have been described as parasitic of SPW (Jansson 1992). Other SPW parasitoids may exist, based on one early report where later instar SPW larvae were investigated to detect possible parasitoid activity when they were found dead in tunnels within sweetpotato vines (Cockerham 1944). More recently, a new ectoparasitic braconid species was discovered that parasitizes both *C. formicarius* and *E. postfasciatus* in Japan (Maeto and Uesato 2007). To date, however, there is no documentation of any of these parasitoids of sweetpotato weevil imparting effective population control in the field, or any indication that research has progressed to the point of considering SPW parasitoid mass-rearing and release to nominate a parasitoid as a candidate for a control strategy.

Other predators

Natural enemy predators of SPW have also been considered, and these may be compatible with other cultural control measures as predators potentially benefit from some habitat preservation (e.g., following use of mulching, intercropping, as discussed previously) during sweetpotato cultivation. Jansson (1992) reviewed reports of a number of natural enemy predators of SPW in Asia and the Americas, primarily of which are certain species of ants. The use of ants has been indicated as a control option for SPW in Cuba, where establishing colonies by transporting them from nearby banana plantations proved effective (Lagnaoui et al. 2000). Similarly, in Papua New Guinea a local practice has been built from grower knowledge of how to use ants to assist in SPW pest control (Sar et al. 2009). Although reports of various predators in association with sweetpotato crops can be found in the literature (e.g., Jansson 1992; Kyereko et al. 2019), it is unclear that the presence of these organisms has any direct or noticeable impact on sweet potato weevil populations. Overall, knowledge of the contributions of natural enemies to SPW control in SSA as part of the routine control measures is nonexistent or otherwise undocumented.

Entomopathogenic bacteria

From a commercial perspective, entomopathogenic bacteria are generally the most successful agents of microbial control (Sanahuja et al. 2011; Arthurs and Dara 2019), however, bacterial-based SPW products are less available, and few studies have even looked at bacteria as potential SPW control options. *Bacillus cereus* biovar. *thuringiensis* (Bt), the most common bacterial species used in microbial insect control, typically is only pathogenic to the larval stages of SPW (Anyanga et al. 2021; Hernández-Martínez et al. 2014). The cryptic lifestyle of the SPW, which spend all of their immature stages inside a plant, make delivering bacterial agents difficult and largely ineffective. There is one registered Bt product (beetleGONE!®, PhyllomBioProducts, Oakland, CA, USA) which lists a number of weevils, including SPW, as being controlled when it is applied to root and tuber vegetables. As nearly all work on SPW control with Bt has been centered on the tactic of developing transgenic plants to deliver an active insecticidal agent, the use of Bt has been further covered in the biotechnology section below.

Separately, we have explored the potential use of bacteria as true entomopathogens in several experiments in the USA or SSA. Researchers at Louisiana State University developed a larval assay to assess the activity of bacterial strains towards *C. formicarius* larvae (Jeff Davis unpublished). We found preliminary activity of 14 bacterial isolates, but the activity was inconsistent. This in vitro work was repeated using the African spp. of SPW, but again, due to the lack of consistency and unclear options for eventual product delivery, further studies were not pursued (Anyanga unpublished).

Entomopathogenic fungi

Entomopathogenic fungi (EPF) are among the most well-studied microbial control options for SPW; most commonly, *Metarhizium* spp. and *Beauveria* spp. have been shown to infect and cause mortality in SPW (Ondiaka et al. 2008; Reddy et al. 2014; Hlerema et al. 2017; Baró et al. 2022). One of the key advantages of entomopathogenic fungi is their ability to infect free living adult SPW. In addition, they are infectious through the cuticle in contrast to bacteria and other insect pathogens which often infect via the oral route. Having the property of being infectious through the insect cuticle allows EPF organisms to be applied using similar methods as those used for chemical pesticides (e.g., by treating vegetation or SPW directly to achieve an ensuing infection and achieve control). Treatments with EPF in a field setting are known to take multiple days, or sometimes weeks, to cause mortality. While this can allow significant crop damage by pests to take place, in the case of *C. puncticollis* following treatment with *M. anisopliae*, and to some degree with *B. bassiana*, even avirulent fungal infection has been shown to reduce SPW fecundity and feeding (Ondiaka et al. 2008), giving the potential for crop protection over time. We have evaluated over 250 strains of *Metarhizium* and *Beauveria* for pathogenicity towards all three *Cylas* spp., finding that most strains were pathogenic and with several demonstrating high levels of virulence in laboratory assays (Keyser unpublished). Greenhouse, screenhouse and field studies also indicated that several of the fungi persist on the plant material for up to 14 days and can remain infectious (Keyser unpublished) thus, EPF as a control strategy within SPW IPM planning may yet hold promise.

Other microbial control agents

Viruses and microsporidia are also important tools for insect microbial control. We have not identified investigations of these microbes in the context of SPW control, indicating an opportunity for research in this area. As entomopathogens, both viruses and microsporidia tend to be host specific (Vega and Kaya 2012), therefore preliminary biology and survey work remains necessary to identify strains that may target SPW.

Chemical control

In this section we will discuss some current options or proposed usage of naturally-derived and synthetic insecticides for mitigating SPW impact and/or its population reduction. Perhaps more so than other control methods considered in this review, the decision to implement chemical control for SPW management has additional potential repercussions on non-target organisms and ecosystems, which must be taken into account prior to a selection. We will consider synthetic compounds, botanicals, semiochemicals and pheromone traps (which are also generally used for monitoring). In addition to being susceptible to SPW, sweetpotato plants serve as hosts for several other insect pests, including other beetles (e.g., wireworm and banded cucumber beetle), whitefly, aphid, and lepidopteran larvae (e.g., sweetpotato butterfly) (Ames et al. 1997; Sorensen 2009; Johnson and Gurr 2016). These varied pests transmit disease to sweetpotato, damage the vegetation as well as the storage roots, leading to reduced harvest quality and quantity. Broad spectrum insecticides are often an important part of controlling this suite of pests. Employed within an IPM framework, insecticides are integrated with other practices (including those outlined in this review) to ensure effective pest management with minimal environmental impact. Insecticides are generally administered via methods such as foliar sprays, drenches, and seed treatments, chosen based on pest characteristics and insecticide type. Adherence to regulations, safety guidelines, and proper resistance management is essential to safeguard food safety, human health, the environment, and the durability of insecticide solutions to choose from.

Synthetic insecticides

In developed countries, chemical control is regularly used to protect sweetpotato from SPW and other insect pests (Dutta et al. 2018; Smith and Hammond 2006) and it is not unusual for chemical insecticide treatments to be applied on a weekly basis. These treatments can take the form of topical sprays, soil treatments, or used to coat root slips before planting. In addition, chemicals from numerous insecticide classes (e.g., carbamates, neonicotinoids, organochlorines, organophosphates, and pyrethroids), have been applied for SPW control (Chalfant et al. 1990; Korada et al. 2010; Taye and Tadesse 2013; Tipu et al. 2021), and have been available for use in developed countries. This control method is not part of routine practice in SSA, especially for smallholder farmers, due to economic considerations, awareness, and availability (*e.g.*, a general insecticide may be present, but not labeled for use with SPW). Furthermore, in SSA there is often a lack of appreciation for the benefits associated with a particular treatment, especially for smallholder growers which leads to a reluctance to invest in chemical pesticides (personal observation).

Botanicals

A number of plant derivatives have demonstrated promising insecticidal activity towards SPW. Although all the components are not always fully defined or characterized, the use of such materials can be viewed as an offshoot of chemical control. Research on pest-controlling botanicals is still a field of interest. Examples of the botanicals which have shown some promise for SPW control are extracts from plant parts, and especially nuts, of the tropical tree

Melia volkensii (Jaoko et al. 2021), yam bean seed extract, karanj oil (Prasad et al. 2022), neem oil (Leng and Reddy 2012; Prasad et al. 2022), and essential oils from various plant sources (Mai et al. 2021). Although many studies on the effects of essential oils are limited to laboratory experiments and have yet to demonstrate effectiveness in the field, this area is continuing to be explored.

Smallholder farmers tend to have a wealth of knowledge regarding their specific locale and will often make use of whatever is readily available to help them with pest control. One such example of this can be seen in Nigeria, where easily formulated plant powders have been tested as insecticidal agents. Powders from three local plants (*Dennettia tripetela*, *Fromomum melegueta*, and *Xylopia aethiopica*) were assayed in various concentrations to determine effects on SPW in a lab setting. Several of the treatments resulted in significant mortality to adult SPW and a concomitant reduction of SPW progeny emergence from an in vitro tuber assay as compared to the control (Nta et al. 2018). Chemistry derived from plant matter (botanicals) such as the examples described above, are an environmentally safe, accessible alternative that could be an attractive pest management approach for SSA. The use of botanicals, however, is not routinely established as a practice against SPW, and sparingly little assessment of its practicality for field applications is available. The amount of effort for production (e.g., labor, growth space and time, expertise needed for final drying, extraction and any particular handling requirements) is also an uncharacterized aspect to consider for any putative botanical application(s). Therefore, it seems that there is no compelling information yet available to conclude that the use of botanicals is a reliable or competitive option for SPW control.

Semiochemicals and pheromone traps

Female SPW release a sex pheromone to attract males, for *C. formicarius* this compound has been synthesized and incorporated into commercially available SPW pheromone traps. These have proven to be an effective tool to attract males for population monitoring and have also been coupled with synthetic insecticides for population suppression via male annihilation techniques (Himuro et al. 2022). Selection of an appropriate trap design option can be important as well (Dilipkumar et al. 2019). Pheromone traps utilizing crotonate esters as suggested by The US Department of Agriculture (USDA), or using (*E*)-2-butenoate esters (Alvarez et al. 1996; Smit et al. 1997; Heath et al. 1992), show successful trapping of male weevils with a minimal rate of escape, reduce sweetpotato crop damage, and are often cost-effective. Research has indicated that the most effective pheromones for trap applications are stereochemically pure (Sureda et al. 2006), this suggests some limitations exist for effective trapping. An additional limitation is that some species-specificity to the pheromones has been identified for the African SPW spp. (Downham et al. 1999; Smit et al. 2001). The pheromones for the African SPW spp. are related to, but distinct from the (*E*)-2-butenoate esters that have been used for the efforts against *C. formicarius* described above. We have observed that pheromone traps which target *C. formicarius* do not attract males of either African species (pers. obvs.). Currently, no commercially available pheromone traps have been developed for *C. puncticollis* or *C. brunneus* which makes monitoring SPW in SSA challenging.

Biotechnological approaches

Several biotechnological options have been looked into for controlling SPW. Currently, for sweetpotato agroecosystems, there are not widely available options for SPW control; however there have been some promising successes in laboratory experiments or localized situations. It is also unclear whether such options would be readily adopted (even if made available) for the farming needs in SSA that are burdened with a limited technical education, infrastructure and economic base. Below we review three approaches that have been investigated: sterile male release, targeted insect-gene suppression with RNAi, and transgenic plants expressing insecticidal proteins.

Sterile insect technique

Of the various biotechnological approaches, this approach has realized the most success. It involves implementation of a population control tactic through large scale release of sterile male SPW. Sterile insect technique for insect control originally achieved notoriety through successes such as the screwworm eradication in the southwestern USA (Knipling 1955). As with that pioneering work, male SPW are sterilized by exposing them to a specific level of gamma radiation. They are then released into the environment and any mating that occurs with these males does not result in progeny, thus reducing overall population levels in the subsequent generation. For SPW control, this strategy has proved effective on particular islands of Japan at various times dating back to 1994 and continues to be implemented in some areas (Himuro et al. 2022). The success of this approach is likely dependent on implementation as a control tactic for a prescribed geography (such as an isolated island) in concert with a more comprehensive IPM program (e.g., that also includes regular pest monitoring, removal of pest reservoir populations nearby) (Himuro et al. 2022). Unfortunately, it is difficult to envision how this technique could be adapted broadly for the situation(s) that exist across SSA; however, it could still be a valuable tool for maintaining low overall population densities in a particular locale, especially if combined with other control measures.

Targeted gene suppression

The potential of using targeted RNA interference (RNAi) for beetle control has been demonstrated for multiple pests (Price and Gatehouse 2008). Essentially this approach involves delivering a species-specific double stranded RNA (dsRNA) molecule targeting the pest insect. When orally ingested, the dsRNA silences an essential gene in the pest and causes mortality. Several studies have investigated the potential of using this method for SPW control and have identified some interesting possibilities for a targeted gene suppression approach (Christiaens et al. 2016; Prentice et al. 2017). Work is still in the preliminary stage for SPW. Several species-specific RNAi targets have been identified and demonstrated positive effects when administered via injection, however, oral uptake has not been as effective (Prentice et al. 2019). Additional research is needed before this technology is ready for use against SPW.

Transgenic plants

Transgenic plants that produce bacterial-derived insecticide proteins have played an important part of insect management in many parts of the world (Que et al. 2010). Since insecticidal proteins tend to be moderately host specific, the first step in working towards a transgenic plant is to identify proteins active against SPW (Rukarwa et al. 2013). Several proteins have been identified as toxic to SPW and it has been demonstrated that they could be used independently (Hernández-Martínez et al. 2020; Prentice et al. 2011). Although transgenic approaches are a routine and widely used component of other crop systems for insect control, similar to the case with a gene suppression strategy, it remains at an early stage for sweetpotato as effective SPW protein toxins or their requisite transgene expression is limiting (Morán et al. 1998; Hernández-Martínez et al. 2020). Thus far, protein expression in the root has been minimal and has not had any significant effect on insect mortality (Rukarwa et al. 2013). Insecticidal proteins are generally active towards insect larvae, thus for the SPW, a successful transgenic plant must produce sufficient protein toxin in the root, where the insect immature life-stages generally occur.

For a control method utilizing transgenic plants, the cost of developing such a tactic and then whether it could be made available and affordable for regions such as SSA should not be overlooked. For example, a recent review found that the average cost of discovery and development efforts through registrations and commercial access for a transgenic trait was upwards of about 115 million USD (Crop Life International 2022). It seems that there may be an inherent challenge in making such technology affordable for a region like SSA, as the companies developing such technology do need to recoup this initial investment during product sales. Additionally, the fact that sweetpotato is largely clonally propagated might present an additional challenge as this would likely not fit with the routine proprietary agreements for employment of transgenic crop technology.

Post harvest considerations

One major hurdle that must be overcome in order for any crop to move from subsistence to commercial farming is post harvest management. In the USA, poor handling practice may result in a loss of more than half of the harvest crop. The two major factors that affect shelf-life are: pest pressure (disease and insect), often exacerbated by environmental conditions in storage; and, mechanical damage incurred during harvest or transport. To prolong storage time a curing process can be implemented whereby the skin of the sweetpotato root is induced to harden, rendering it less susceptible to physical damage and entry of disease organisms—this can extend the shelf life up to 6 months. The curing process is initiated by keeping the freshly-harvested roots at a temperature of 29 to 30 C and high relative humidity (90–95%) for four to 7 days, often followed by a drop in storage temperature to just under 13 C (Ray et al. 2010; Estes 2009). It has also been noted that maintaining proper ventilation during the curing process is key to ensure the necessary exchange of carbon dioxide and oxygen which takes place by the stored roots (Smith et al. 2009; Louisiana Insect Pest Management Guide 2023). In the USA, the curing step, when implemented soon after harvest, has been instrumental in obtaining a prolonged shelf-life and optimized flavor for harvested roots; it has been estimated that up to 90% of the sweetpotato crop in the USA undergoes a curing step (Estes 2009). However, extended storage provides additional opportunities for SPW infestation and damage. Similar to SPW mitigation in the field, an IPM toolkit is necessary during post harvest; SPW can infest the sweetpotato roots during this period of postharvest storage as well (Edmunds et al. 2008; Louisiana Insect Pest Management Guide 2023). In the USA this IPM toolkit includes selection of resistant varieties, monitoring programs, and regular insecticide application during storage.

In SSA, growers—especially subsistence farmers—face several challenges related to postharvest management. Often temperature and ventilation controlled facilities are not available. As an alternative, a pre-harvest curing option has been explored where the plant canopy is removed up to 14 d prior to actual harvest (Tomlins et al.

2010; Sugri et al. 2019); this practice is known as "dehaulming" and may achieve curing as the environmental conditions of elevated temperature without drying are approximated. In SSA, root injury may occur at harvest when using manual tools, this is further accentuated during transport as roots roots often moved in large sacks; this method for transport has been found to incur more root injury than the use of boxes or crates (Ray et al. 2010; Tomlins et al. 2010). In countries where such recommended transport and storage conditions for harvested sweetpotato roots are less readily available, there have been several low cost storage techniques devised such as storage in pits or heaps (Tomlins et al. 2010), however the shelf life extension from such methods does not approach that of the standard practice in developed countries. In such cases, retailers often seek to sell the roots as soon as possible rather than arranging for storage (Tomlins et al. 2010). This is also true for subsistence purposes where roots are often left in-ground for storage and harvested piece-meal, as the short shelf-life is a major constraint for seeking to market the sweetpotato crop. In situations in which a curing step is not possible, weevil control in the field is even more critical to avoid population build up which may affect subsequent crops—cultural practices such as sanitation and re-ridging (discussed above) are especially important. As growers move towards early harvest, curing and extended storage, additional control strategies must be implemented, such as monitoring and removal of infested material, chemical or biological control applications, and selection of resistant varieties. Having a multifaceted strategy for post harvest management is crucial to protect crop yield.

Should the IPM strategies for SPW in SSA look like that of other regions?

IPM remains essential to pest control for modern agriculture and can provide sustainable and environmentally sensible solutions to address a variety of pest situations growers face. For SSA, however, an a priori focus on commodity and technology opportunities that benefit from IPM may be misaligned with the smallholder farmer perspective where broader objectives often exist, balancing any production goals with subsistence needs (Orr 2003). This same individualized perspective which exists also suggests an inherent IPM challenge for a region with a preponderance of smallholder farmers. For example, individual IPM approach(es) could be compromised by other (e.g., neighboring) practices that may or may not be in place, or by a lack of compliance to an agreed-upon coordinated plan. This concept of an adverse impact from other grower practices nearby has been identified as a concern even in larger farming situations and in the developed world (e.g., in weed management) (Ervin and Jussaume 2014; Ervin and Frisvold 2016).

While some "success stories" have been demonstrated across various regions of Africa in the past when IPM has been practiced against other agricultural insect pest or disease problems (Kiss and Meerman 1991; Nwilene et al. 2008; Norton et al. 2019) problems exist in SSA which interfere with grower implementation of IPM. Of concern are aspects of IPM not being designed for current SSA considerations such as: a lack of cost-effectiveness, not being adaptable to farming practices that are in place, not being supported with requisite training and education, being presented with weak incentives for adoption, lacking the region-specific strong research association, and outreach challenges centered around limitations in the existing research and extension systems (Parsa et al. 2014; Oyediran 2023). Oyediran (2023) has considered these IPM challenges for SSA in the context of other crop systems, however, those same problems noted likely interfere with IPM for sweetpotatoes as well. For example, small scale farming and other aspects of routine sweetpotato farming practice(s) in SSA have been largely driven by local or even family subsistence economics as well as very individualized experience and training; it has not been primed to benefit from the consideration of new inputs and information regarding control options. Compounding this status, a recurrent problem which has been noted by others is that there are insufficient training programs and support systems that are tailored to consider the needs of SSA growers (Kiss and Meerman 1991; Orr and Ritchie 2004; Okonya et al. 2014; Parsa et al. 2014).

Also, the extensive geography available in Africa and the impact of differing pest biology across regions may permit the development of resistance to a given local control practice which could eventually impact adjoining areas. This is a likely additional challenge for IPM consideration in SSA. For example, to mitigate the spread of SPW in areas of the USA, individual state regulations have been implemented which restrict the distribution of sweetpotato material from fields where weevils have been observed. To avoid potential produce distribution restrictions, growers rely on careful monitoring, and proactive treatments of chemical pesticides in the field and storage. These policies along with the limited distribution of SPW in the USA allow for an approach that may lead to eradication of the pest within the limited geography. However, applying these same principles to SSA is unlikely to be effective due to several factors: (i) SPW is native to Africa, is broadly distributed, and growing conditions allow for continuous SPW population growth across regions that rely on sweetpotato as a primary crop; (ii) tools are not available for consistent monitoring and implementation or they are of restricted distribution; (iii) implementing and enforcing policies that restrict food production in subsistence farming is unlikely to be adopted or supported by growers and is potentially unethical.

IPM is, by its very nature, a dynamic process, dependent upon changing external factors, available choices for control and implementation options (e.g., challenging situation whereby growers may not have continued access to a pesticide; this can impact control options in both developed and developing countries) and, importantly, the assessment of the changing pest status. In the absence of well-established economic thresholds or models applicable to the locale-specific grower situations present in SSA, some of the routine IPM practices of the developed world (refer to Fig. 2) seem less advisable for SSA. What is included in SPW IPM and what defines it being successfully implemented is going to continue to be different in developed and developing countries. For instance, the aforementioned examples of success in developed countries (e.g., Japan and the U.S.) have been specifically tied to geographical limitations (naturally in place or "artificially" imposed by quarantine) working against the pest population along with supportive regulations, infrastructure, and monitoring tools. What successful SPW IPM looks like for SSA can not benefit as easily from those exact practices.

Recommendations for sweetpotato weevil IPM in SSA

For many years it has been noted that amongst IPM options for SPW in SSA, the cultural control measures can be seen as a continuing and suitable path forward (Smit 1997b). Clearly complementary to this would be the use of cultivars with some measure of resistance to SPW. Host plant resistance is also favorable because it (i) tends to be specific to the pest of concern, (ii) is persistent each time the crop is planted, (iii) is easily adopted if the cultivars are made readily available, (iv) is environmentally friendly, and (v) can be expected to be compatible with other cultural techniques that may already be in place. Cultural controls, which can be seen as largely preventative, are applicable for SSA SPW control irrespective of the dynamics of the pest itself or other external factors. In addition to always being applicable, these practices are the most promising due to their being practical and more likely to be well-received by the smallholder growers. Furthermore, they involve a lower cost of investment, and benefit from an ease of associated training for their implementation. Confirmation of this exists in the fact that several such cultural control measures are currently part of routine practice in SSA (Fig. 2). Opportunities do exist, however, for an even more effective deployment of these practices in SSA, such as in these recommended areas:

- Field sanitation measures to better ensure removal of all prior sweetpotato material (above and belowground) nearby the area to be newly planted; common practice relies on "volunteer plants" to supplement the next cycle of planting (Ebregt et al. 2004), which is incompatible with field sanitation or burial of plant debris which can still allow for pest problem development.
- Increase availability and use of clean planting material. Even without access to a centralized or large-scale certification-type supply, there are two cultural practices which look extremely promising to impact a locally generated source of clean material. First, use of cuttings from younger stems which have a decreased chance of already harboring weevils (AVRDC 1991; Jansson and Raman 1991, p. 145; Smit and Matengo 1995). Second, use of the Triple S method ("Storage in Sand and Sprouting") for preparing cuttings needed for subsequent planting cycles (Hundayehu et al. 2022; Namanda et al. 2013).
- Keeping a separation between plots of sweetpotato either spatially or through the use of barrier plantings, or temporally through crop rotation.
- Early harvesting at 4 or 5 months after planting. If coupled with improved storage options, this method (in combination with the above practices) could significantly reduce SPW damage in SSA.

Furthermore, for SSA to reduce the threat of SPW we recommend the following areas of focus:

- The foundational practices described need to be more broadly adopted and alignment achieved on best practices to implement for given locale(s).
- Adoption or development of reliable and cost-effective insecticide treatment(s) (chemical or microbial), requiring minimal (ideally only one) application, while providing season long control if other foundational practices and cultural control methods are in place. For example, current research on potential microbial control organisms could lead to a treatment applied using an augmentation strategy which would establish the microbial control agent in the environment of the roots throughout the growing season. At a minimum, insecticidal treatments should be safe, easy to use and provide consistent SPW population reduction.
- Communities can support neighboring efforts to achieve crop sanitation goals, align on and promote the best practices, share expertise, in particular with regard to pest identification and provide informal training for adjacent farmers in need of such information.

- Provision of picturesque infographic-type education materials (unhindered by language barriers) regarding SPW biology and available control practices which could be influential to IPM implementation if made readily available for the smallholder farmers.
- Increased digital access to real-time insect pest diagnostics (Bello-Bravo et al. 2022; Tamò et al. 2022).
- Academic or industry-related research and development efforts should focus on cost-effective treatments to apply to the sweetpotato plants during the planting period (as noted above), and data collection and dissemination on best practices being adopted and successes realized (e.g., avoid extensive R&D efforts toward use of predators, parasitoid Biological control measures which are perceived to be of low likelihood to successfully implementing the near-term).

Conclusions

Sweetpotato weevil is a difficult pest to control, however, we hold that if the above recommendations can be more effectively implemented, in concert with cultural control practices already in place, such a multi-faceted strategy could recognize positive results for SPW management in SSA. Concomitantly, the attention to SPW management could achieve improvements in both the quantity and quality of sweetpotato production. We also concur with others who have indicated that the inherent challenges which exist in SSA agriculture (Parsa et al. 2014) might render it non-ideal to have the IPM plans in SSA (in this case for SPW) mimic programs from other developed countries (Oyediran 2023). Rather, we advocate the IPM plans which evolve for SSA should reflect the practice options that exist for a given locale and build off of more of a localized and coordinated approach to IPM awareness and implementation. This direction could then be better adopted and sustained and become part of cultural/social changes that perhaps could allow for other IPM practices to become options in the future.

Abbreviations

Bt	*Bacillus thruingiensis*
C.b.	*Cylas brunneus*
C.f.	*Cylas formicarius*
C.p.	*Cylas puncticollis*
EPF	Entomopathogenic fungi
IPM	Integrated pest management
SPW	Sweetpotato weevil
SSA	Sub-Saharan Africa

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Competing interests

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