Chapter 1

General Introduction

1.1 Push-pull: an appropriate component of sustainable integrated pest management

1.1.1 Push-pull as a type of habitat management

Push-pull, which is being promoted as part of an integrated pest management (IPM) approach to control *Eldana saccharina* Walker (Lepidoptera: Pyralidae) in sugarcane (*Saccharum officinarum* L. (Cyperales: Poaceae)), is a specific type of habitat management. In push-pull, components of the agroecosystem act as sinks, attracting pests, while others repel pests (Gurr *et al.*, 2004a; Cook *et al.*, 2007). Habitat management forms part of the conservation biological control approach to pest management (Ehler, 1998). In conservation biological control, the agroecosystem is manipulated to protect and enhance locally occurring natural enemies, thereby reducing the effect of pests on the crop (Ehler, 1998).

The practice of habitat management to reduce the impact of crop pests can be traced back thousands of years to innovative farmers in Asia (Gurr *et al*., 2004b). In China, to this day, farmers provide straw shelters for spiders, a practice which dates back 2000 years. In 18th century Burma, farmers provided walkways for predacious ants between citrus trees to allow them to feed on scale insects (Gurr *et al*., 2004b). Similarly, farmers in Africa have been practicing intercropping and trap cropping, both forms of habitat management, for centuries (Abate *et al*., 2000). Habitat management can also be classified as a form of cultural control (New, 2005). Cultural control is a broad term used to describe all agronomic activities associated with the crop, including temporal, spatial and biological considerations (New, 2005), that makes the environment unfavourable for the pest. Cultural control is not a therapeutic but rather a proactive approach to pest management (Dent, 1995; Van den Berg *et al*., 1998).

High-intensity crop monocultures have become the dominant form of agriculture in much of the developed and parts of the developing world. However, such agriculture is losing its attractiveness due to the health and environmental risks associated with pesticide use, pesticide resistance and increased cost of fossil fuels (Pretty, 2005). This has renewed interest in more sustainable practices such as habitat management (Gurr *et al*., 2004a; Pretty, 2005). Monocultures constantly undergo frequent, intense disturbance regimes which makes them unfavourable environments for natural enemy populations (Landis *et al*., 2000). Plant diversity is important for stability of insect communities in agricultural ecosystems, and habitats adjacent to the crop and corridors of non-crop vegetation can support diverse natural enemy communities in agroecosystems, and even contribute to ecosystem services provided by the agricultural environment (van Emden and Williams, 1974; Landis *et al.*, 2000; Fiedler *et al.*, 2008). This forms the basis of a conservation biological control–habitat management approach to pest management in various crop systems. There are many examples of such studies showing positive results (Landis *et al.*, 2000; Ratnadass *et al.*, 2011). The latter do however warn that vegetational diversification does not always reduce the incidence of pests and diseases, because of the wide host range of some pests and pathogens.

One of the most successful case studies of conservation biological control and habitat management is the push-pull strategy developed in Kenya for the control of lepidopteran stem borers of maize (*Zea mays* L. (Cyperales: Poaceae)) (Khan *et al.*, 2001; Khan and Pickett, 2004; Khan *et al.*, 2011). The push-pull theory was first formalised by Miller and Cowles (1990) in their work on the onion maggot (*Delia antiqua* Meigen (Diptera: Anthomyiidae)) where they referred to it as stimulo-deterrent diversion (SDD). The push-pull strategy in pest management was reviewed by Cook *et al.* (2007). Push-pull systems have the potential to contribute to IPM approaches for controlling pests as they emphasize the importance of understanding the biology and ecology of the pest (Hassanali *et al.*, 2008; Conlong and Rutherford, 2009). IPM and ecological pest management solutions are seen as the only sustainable way of controlling pests (New, 2005; Pretty, 2005).

1.1.2 Push-pull in practice: a case study from Kenya

In their review of push-pull for pest management, Cook *et al.* (2007) documented numerous examples of push-pull strategies which have been developed in a range of agricultural situations. These include subsistence grain crops, commercial cotton and potato production, glasshouse chrysanthemums, forestry and medical and veterinary pest management. Upon closer scrutiny of these push-pull strategies however, it became clear that very few have been adopted and successfully implemented at field level (Cook *et al.*, 2007). Numerous reviews of agroecological strategies for pest management note that because of the more complex nature of integrated pest management systems such as push-pull and habitat management, adoption of such technologies is poor (Gurr *et al.*, 2004b; Shelton and Badenes-Perez, 2006; Cook *et al.*, 2007; Ratnadass *et al.*, 2011). However, according to Gurr *et al.* (2012), the uptake of agroecological pest control measures often results in visually pleasing improvements to the farm landscape, and this may make it easier for farmers do demonstrate that they are making a tangible effort to reduce pest problems in a biodiversity-based manner. If, as is suggested by Vanclay (2004), farmers generally want to ‘do the right thing’, then pest solutions based on biodiversity, such as push-pull and habitat management, may in fact be appealing to farmers.

A clear exception to the tendency of non-implementation, is the push-pull strategy developed by ICIPE (The International Centre for Insect Physiology and Ecology) for small-scale maize farmers in Kenya (Khan *et al.*, 2001; Gatsby Charitable Foundation, 2005). Building on research on the role played by wild grasses as natural hosts for stem borers and their natural enemies (Khan *et al.*, 1997a; Khan *et al.*, 1997b; Schulthess *et al.*, 1997), researchers at ICIPE, together with their partners (Rothamsted Research, Kenyan Agricultural Research Institute), have developed the push-pull system for the control of lepidopteran stem borers and the parasitic *Striga* weed (*Striga hermonthica* (Del.) Benth. (Lamiales: Scrophulariaceae)) on small-scale maize farms (Khan *et al.*, 2006b; Hassanali *et al.*, 2008; Vanlauwe *et al.*, 2008). The push-pull strategy has been adopted by over 30 000 farmers in East Africa, where it is directly contributing to increased cereal yields, livestock production, soil fertility, household income and empowerment of women (Khan *et al.*, 2011).

Push-pull makes use of plants of economic importance planted as intercrops and trap crops for stimulo-deterrent diversion of maize stem borers and to increase parasitism of the stem borers (Figure 1.1) (Khan *et al.*, 1997b). The plants used in this system are also used for livestock fodder in eastern Africa. This integrated system not only reduces damage to maize from stem borers, but also aids in the control of *S. hermonthica* and has beneficial effects on soil quality. Silverleaf desmodium (*Desmodium uncinatum* (Jacq.) DC. (Fabales: Fabaceae)) or molasses grass (*Melinis minutiflora* P. Beauv. (Cyperales: Poaceae)) are intercropped with maize as repellent plants (push) (Khan *et al.*, 1997b; Khan *et al.*, 2001). *Desmodium uncinatum* and *M. minutiflora* also attract natural enemies (parasitoids) into maize fields to increase parasitism of the stem borers (Khan *et al.*, 1997a). Napier grass (*Pennisetum purpureum* Schumach. (Cyperales: Poaceae)) is planted as an attractant (pull) trap plant as a border crop and acts as an alternative host to egg-laying moths. It is more attractive to gravid moths than maize and larval survival on Napier grass is much lower than on maize (Khan *et al.*, 2006a).

On-farm field trials using this strategy have shown statistically significant increases in maize yields across ten districts in Kenya, involving more than 1500 farmers (Khan *et al.*, 2001; Khan *et al.*, 2011). Yields increased from approximately 1 ton/ha to 3.5 ton/ha (Khan *et al.*, 2010). These benefits were further illustrated by a 7-year economic study of farmers who planted push-pull fields alongside control fields of maize monocrops and maize-bean intercrops. This study showed that maize yields, gross margins and returns on investment in land and labour were significantly higher in push-pull fields than in conventional systems (Khan *et al.*, 2008c).

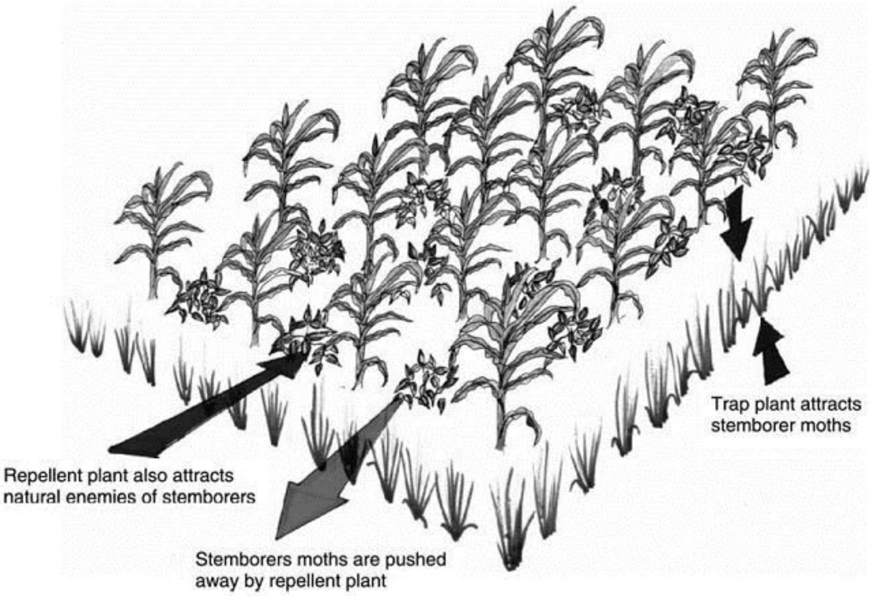


Figure 1.1. Diagram of the push-pull strategy for stem borer management in maize fields in Kenya. Arrows indicate movement of insects: stem borers are 'pushed' away by repellent plants (e.g. *Desmodium uncinatum* or *Melinis minutiflora*) and 'pulled' by attractant trap plants (*Pennisetum purpureum*). Parasitoids are pulled into the fields by the repellent plants (From Khan *et al.* 2011).

1.1.3 The need for an effective, sustainable control strategy for Eldana saccharina

Successes in sustainable pest management approaches, particularly the Kenyan push-pull strategy, motivated researchers at the South African Sugarcane Research Institute (SASRI) to investigate the possibility of a similar system for the control of *E. saccharina* in sugarcane (Conlong and Kasl, 2000; Kasl, 2004). A knowledge-based agroecological approach to pest management integrates well with the biological control programme at SASRI (Conlong, 1994a; Conlong, 1997a) as well its more recent area-wide integrated pest management (AW-IPM) initiative (Conlong and Rutherford, 2009; Rutherford and Conlong, 2010). Constraints to the successful establishment of biological control agents for *E. saccharina* in sugarcane (Conlong, 1997a) indicated that a habitat management system aimed at increasing the efficacy of natural enemies of *E. saccharina* was required (Conlong and Kasl, 2001; Conlong and Rutherford, 2009).

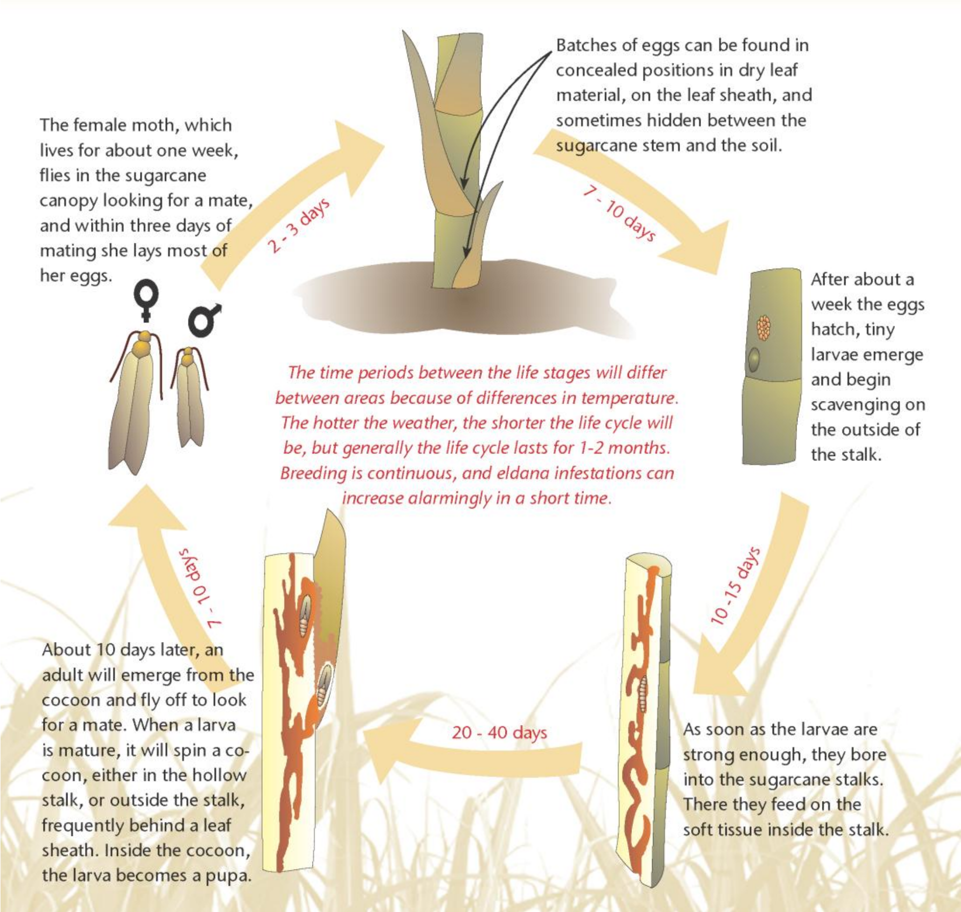
1.1.3.1 Distribution, pest status and biology

Eldana saccharina is indigenous and widespread across most of sub-Saharan Africa (Girling, 1972; Atkinson, 1979, 1980). It is a polyphagous stem borer which favours monocotyledonous host plants from the Poaceae, Cyperaceae, Typhaceae and Juncaceae (Girling, 1972; Atkinson, 1979; Polaszek, 1997; Conlong, 2001; Mazodze and Conlong, 2003). *Eldana saccharina* was first recognised as a major crop pest in West Africa, where it infested maize and sorghum (*Sorghum bicolor* (L.) Moench (Cyperales: Poaceae)) (Bosque-Pérez and Schulthess, 1998). It has subsequently attained pest status on three major crop plants in Africa: sugarcane (Carnegie, 1974; Conlong, 1994a; Keeping, 1995), maize and sorghum (Girling, 1978; Bosque-Pérez and Mareck, 1991; Bosque-Pérez and Schulthess, 1998; Atachi, 2005). *Eldana saccharina* is recognised as an important pest of sugarcane in western, eastern and southern Africa (Carnegie *et al.*, 1976; Conlong, 1994a; Conlong and Mugalula, 2001; Mazodze and Conlong, 2003). However, the distribution and pest status of *E. saccharina* across Africa is not uniform and this species exhibits differing biotypes across its range (Conlong, 1997b, 2000; Atachi, 2005; Assefa *et al.*, 2006). Recent surveys have shown the South African range of *E. saccharina* to be increasing from the warmer coastal regions to regions further inland (Assefa, 2008; Assefa *et al.*, 2009; Webster *et al.*, 2009). This poses an increased threat to sugarcane production and a potential new threat to maize production in South Africa.

Eldana saccharina was first identified as a pest in sugarcane in South Africa on the Umfolozi flats of KwaZulu-Natal in the 1940s (Dick, 1945). After this initial outbreak pest incidence declined, however, by the 1970s, *E. saccharina* was once again on the increase (Carnegie, 1974). This pest is now recognised as the most injurious insect pest of sugarcane in South Africa (Keeping, 1995; Goebel and Sallam, 2011). Although estimates vary, direct economic loss due to damage by *E. saccharina* is valued at approximately R60 million per annum (Keeping, 1995; Way, 2004), and substantial control of this pest has still not been achieved (Singels *et al.*, 2011; 2012)..

Eldana saccharina causes damage to sugarcane by completing the larval stage of its lifecycle inside the stem, where it is protected from natural enemies (Dick, 1945). Larval feeding damages stalk tissue, reduces sucrose levels and causes reduced plant health and overall yield (Dick, 1945;

Goebel and Way, 2003). Once present, pest numbers rapidly increase in infested sugarcane fields especially as the crop ages. This has been hypothesized to be a result of a release from natural enemies in the sugarcane habitat (Conlong, 1990), as is the case with stem borers in other cereal crops (Mailafiya *et al.*, 2011). The lifecycle of *E. saccharina* is summarised in Figure 1.2. and more details on the biology of this pest can be found in Dick (1945), Atkinson (1980) and Carnegie and Leslie (1990).



Batches of eggs can be found in concealed positions in dry leaf material, on the leaf sheath, and sometimes hidden between the sugarcane stem and the soil.

After about a week the eggs hatch, tiny larvae emerge and begin scavenging on the outside of the stalk.

As soon as the larvae are strong enough, they bore into the sugarcane stalks. There they feed on the soft tissue inside the stalk.

About 10 days later, an adult will emerge from the cocoon and fly off to look for a mate. When a larva is mature, it will spin a cocoon, either in the hollow stalk, or outside the stalk, frequently behind a leaf sheath. Inside the cocoon, the larva becomes a pupa.

The female moth, which lives for about one week, flies in the sugarcane canopy looking for a mate, and within three days of mating she lays most of her eggs.

The time periods between the life stages will differ between areas because of differences in temperature. The hotter the weather, the shorter the life cycle will be, but generally the life cycle lasts for 1-2 months. Breeding is continuous, and eldana infestations can increase alarmingly in a short time.

Figure 1.2. The lifecycle of *Eldana saccharina* in sugarcane (from SASRI, 2005).

Eldana saccharina has been found to favour indigenous host plants over sugarcane in preference trials (Kasl, 2004). Since it prefers its indigenous host plants, questions arise: why did the insect undergo this apparent ‘host-plant shift’ (Conlong, 1990) onto a less favourable host, and why has *E. saccharina* become such a ‘successful’ insect on a host plant which it does not favour above its natural host plants?

Due to rapid expansion of sugarcane agriculture in KwaZulu-Natal in South Africa in the early 20th century, wetland areas were converted to sugarcane fields (Osborn, 1964). These wetlands would have been the original habitat of *E. saccharina* since the Cyperaceae are the dominant plant species in these habitats (Atkinson *et al.*, 1981). It is hypothesised that *E. saccharina* adapted to sugarcane due to a number of reasons:

- a reduction in availability of natural host plants
- sugarcane is a suitable alternate host as it is marginally more nutritious than the *Cyperus* spp. favoured by *E. saccharina (Cyperus papyrus* L. and *C. dives* Delile (Cyperales: Cyperaceae))
- sugarcane provides copious cryptic oviposition sites which suits the adults' oviposition habits (Conlong *et al.*, 2007) and
- sugarcane is a member of the Poaceae family, the same family as other known wild hosts of *E. saccharina.*

Although *E. saccharina* is an indigenous African insect, and its new environment is often found adjacent to wetlands where its populations persist in their natural host plants, this insect has experienced natural enemy release in the new crop environment (Conlong, 1997a). The natural enemies of *E. saccharina*, particularly the parasitoids, have not followed this insect into its newly adopted environment in sugarcane fields (Conlong and Hastings, 1984; Conlong, 1994b). The natural enemy release hypothesis states that when an organism shifts onto a new host plant or moves into a non-native environment it may undergo natural enemy release, i.e. its natural enemies are no longer present in the new environment and the organism undergoes an increase in population because it is no longer under biological control (Williamson, 1996; Keane and Crawley, 2002). Conlong (1990; 1994b) described the ecology and phenology of *E. saccharina* and its parasitoids in *C. papyrus.* The population numbers of parasitoids peak just after those of *E. saccharina*, and once parasitoids reach high numbers, the populations of *E. saccharina* decrease. This indicates that these parasitoids are keeping *E. saccharina* populations in equilibrium (Conlong, 1990; Conlong, 1994b). However, parasitism of *E. saccharina* is very low in sugarcane, and where parasitoids have been released into sugarcane fields, establishment has been poor, despite them being common in wild hosts such as *C. papyrus* (Conlong and Hastings, 1984; Conlong, 1997a). One explanation for this is that when *E. saccharina* feeds on sugarcane, the plant does not release kairomones or herbivore-induced plant volatiles (HIPVs) that parasitoids cue into (Conlong and Kasl, 2001; Smith *et al.*, 2006). Kairomones are used by parasitoids to locate suitable hosts (Brown *et al.*, 1970; Bruce *et al.*, 2005). When these are absent, the parasitoids fail to recognise their hosts in the new habitat. This phenomenon was also described in maize (Turlings *et al.*, 1990), and more recently it has been shown that commercially bred maize hybrids do not emit kairomones but that landrace varieties do, presumably because of selective breeding for other traits (Tamiru *et al.*, 2011). A similar loss in ability to emit kairomones has been hypothesized to be the case in sugarcane (Conlong and Rutherford, 2009). Smith *et al.* (2006) showed that sugarcane and *C. papyrus* infested with *E. saccharina* emit very different volatile profiles. The parasitic wasp *Goniozus indicus* Ashmead (Hymenoptera: Bethylidae) found attacking *E. saccharina* in *C. papyrus* umbels in South Africa (Conlong, 1990; Conlong, 1994b) responds only to *C. papyrus* infested with *E. saccharina* and not to sugarcane infested with *E. saccharina* (Smith *et al.*, 2006). The absence of parasitoids in sugarcane, because of non-recognition of HIPVs, may explain why populations of *E. saccharina* increase rapidly in sugarcane, and reach higher densities than those in the natural wetland habitats (Conlong, 1994b; Conlong and Kasl, 2001).

Surveys of stem borers in cultivated and wild habitats have contributed to a better understanding of the interactions between pests, their host plants and their natural enemies for a number of pest stem borers (Matama-Kauma *et al.*, 2008; Assefa *et al.*, 2010; Govender *et al.*, 2011; Mailafiya *et al.*, 2011). Assefa *et al*. (2010) described the stem borer-natural enemy complex of sugarcane in small-scale farmers' fields and associated natural vegetation in Ethiopia. They found that the close association of sugarcane and wild hosts indicated that habitat management would be a promising method for managing stem borers in sugarcane fields. Govender *et al*. (2011) found that stem borers were parasitized by the gregarious parasitoid *Cotesia sesamiae* Cameron (Hymenoptera: Braconidae) in wild hosts but not in sugarcane. This kind of ecological information is important for the development of habitat management programmes to enhance the effectiveness of parasitoids in regulating stem borer populations in crops and to better understand the role of wild habitats as a potential source of pests and natural enemies (Khan *et al.*, 1997b; Le Rü *et al.*, 2006b).

1.1.3.2 Current control measures

Current recommendations for the control of *E. saccharina* are made within an IPM framework (SASRI, 2005). IPM recommendations promote a holistic approach to pest management under four main focus areas: host plant resistance, chemical control, cultural control and biological control (Dent, 1995). IPM has a number of different definitions, however Kogan (1998: 249) provided the following definition which encompasses the most common interpretations of IPM:

> "IPM is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment."

SASRI's recommendations for control of *E. saccharina* are summarised in *Guidelines and Recommendations for Eldana Control in the South African Sugar Industry* (SASRI, 2005). Webster *et al.* (2005; 2009) provided a case study of farm-level implementation of SASRI's IPM guidelines for *E. saccharina* control in the Midlands North area of KwaZulu-Natal.

Current control measures emphasize the importance of good crop management i.e. cultural control. Health of the crop and correct soil moisture nutrient levels are important for reducing the impact of *E. saccharina* on the crop (Carnegie, 1981). Stringent field hygiene and correct variety choice are also important tools for management of this pest (Carnegie, 1981). The age at which the sugarcane is harvested plays an important role in management of *E. saccharina*, as it is known to reach high levels in older cane (Leslie, 2004).

Where farmers may need to carry over older crops which already have high *E. saccharina* infestations the use of chemical control if recommended. This often happens because sugar mills have closed before the harvesting process could be completed. The only insecticide currently registered for use against *E. saccharina* is alpha-cypermethrin (Fastac®) (Leslie, 2009). IPM recommendations for chemical control of this pets require limited and careful use of insecticides to prevent build-up of insecticide resistance and to reduce the negative impacts of insecticides on the environment (Pretty, 2005). Thus farmers are advised to monitor their crop for *E. saccharina*, particularly the older crop, since this can assist them in making informed decisions regarding the use of insecticides (SASRI, 2005; Leslie, 2009).

The third focus area of IPM, biological control, is currently not included in *E. saccharina* management guidelines. SASRI has however, since 1975, been involved in research into biological control measures for *E. saccharina*, and this work has been reviewed in numerous publications (Carnegie and Leslie, 1979; Conlong, 1994a; Conlong, 1997a; Conlong and Rutherford, 2009). A lengthy and thorough biological control programme investigating wild host plants and natural enemies of *E. saccharina* has laid a firm foundation of biological and life history knowledge on this pest and its natural enemies (Conlong and Hastings, 1984; Carnegie and Leslie, 1990; Conlong, 1990; Conlong, 1994b; Hearne *et al.*, 1994; Conlong, 1997a).

Several potential biological control agents have been identified and reared in the Insect Unit at SASRI, however very little successful establishment or parasitism has been recorded (Carnegie and Leslie, 1979; Conlong, 1994a). The biocontrol programme at SASRI was based on two types of biological control (Conlong and Hastings, 1984): new association biocontrol (Hokkanen and Pimentel, 1989) and modified classical biocontrol (Conlong, 1990). These two approaches and their successes and failures are reviewed by Conlong (1997a). One criticism of the initial attempts at identifying suitable biocontrol agents for *E. saccharina* was that efforts were focused on identifying parasitoids which attacked this pest in the cultivated crop environment which was the 'invaded' one and not the natural one, and thus devoid of natural enemies (Conlong, 1994b). Subsequently, more work has been done searching for natural enemies of *E. saccharina* in its indigenous host plants in wetland habitats in South Africa (Conlong, 1990) and in other African countries, where these associations have developed over time (Conlong, 2000).

Conlong (2001) suggested that knowledge of the tritrophic system of host plant-stem borer-parasitoid which has been developed through the biocontrol research programme at SASRI, should be utilised to develop a habitat management approach. Through this the agroecosystem could be manipulated to favour the establishment of indigenous natural enemies and increase the chances of these natural enemies finding *E. saccharina* inside cane fields.

When considering the natural history of *E. saccharina*, its widespread distribution throughout sub-Saharan Africa, its wetland host plants and its cryptic habits in sugarcane, it is apparent that conventional pest control tactics are unlikely to succeed in reducing the damage caused by this pest to sugarcane.

1.1.3.3 Development of a push-pull strategy

Research into the biology and wild hosts of *E. saccharina* formed the basis of the habitat management programme for this pest (Atkinson 1979, 1980, Conlong 1990). Conlong and Kasl (2000) reported on the initial phases of the habitat management research programme where the focus was on three aspects:

- better understanding the role of parasitoids for control of *E. saccharina* at different life stages and on different host plants, both wild and cultivated
- details of habitats in which parasitoids seemed most prevalent/active to form the basis of a habitat management system
- investigations into semiochemicals and the attractant/repellent properties of plants which could be incorporated into the sugarcane agroecosystem to increase the efficacy of parasitoids and reduce stem borer infestations (push and pull plants).

A number of potential push (repellent) and pull (attractant) plants were tested for suitability in a habitat management system, using both laboratory and field experiments (Kasl, 2004; Barker, 2008). The project also investigated the effect of candidate push and pull plants on *Xanthopimpla* *stemmator* Thunberg (Hymenoptera: Ichneumonidae), a pupal parasitoid of *E. saccharina* (Conlong and Kasl, 2001; Kasl, 2004).

Cage trials to test trap plants indicated that both *P. purpureum* and *S. bicolor* were attractive for oviposition by *E. saccharina* female moths (Kasl, 2004). Field trials indicated that *S. bicolor* would be the best trap crop, but its potential to compete with sugarcane was a concern (Kasl, 2004). On-farm trials also confirmed the strong attractant properties of *C. papyrus*, an indigenous host plant of *E. saccharina.* Sugarcane fields adjacent to stands of *C. papyrus* showed significantly reduced damage compared to fields which didn't have *C. papyrus* growing adjacent to them (Kasl, 2004). Larval and moth choice experiments confirmed that *C. papyrus* is indeed a favoured host of *E. saccharina* (Kasl, 2004; Conlong *et al.*, 2007). In these choice experiments, *C. dives*, a well known wild host of *E. saccharina*, was also chosen more frequently than sugarcane by larvae and moths.

Kasl (2004) and Conlong *et al.* (2007) reported that female moths do not always show strong preferences for specific host plants but that they did however exhibit a hierarchical preference for host plants, with sedge species favoured over sugarcane and wild grass species. This was observed in both olfactometer and cage trials. It was shown in these trials that female *E. saccharina* moths chose cryptic oviposition sites and oviposited on plants older than six months, and that the neonate larvae are more 'choosy' about their host plants and may disperse to suitable feeding sites upon eclosion (Conlong *et al.*, 2007). This has implications for the selection of push and pull plants since these have to be tested not just on ovipositing females, but also on dispersing neonate larvae (Conlong *et al.*, 2007; Barker, 2008). These observations confirmed that an understanding of pest behaviour allows informed decisions to be made on the timing of planting of pull plants (for example, to ensure that they are more than six months old) to be most suitable for oviposition when moth populations peak (Atkinson, 1982).

The effect of push and pull plants in a habitat management system on parasitoids, was identified as a priority area of study (Conlong and Kasl, 2000; Kasl, 2004). Subsequent field trials showed that parasitism of a suite of stem borers namely *E. saccharina, Chilo partellus* Swinhoe (Lepidoptera: Crambidae) and *Sesamia calamistis* Hampson (Lepidoptera: Noctuidae) increased in plots adjacent to stands of *S. bicolor* as compared to control plots where *S. bicolor* was absent (Kasl, 2004). *Eldana saccharina* feeding on sugarcane does not result in production of the same volatiles as feeding on its wild host, *C. papyrus* (Smith *et al.*, 2006). Increasing plant diversity around the crop by planting species such *S. bicolor* and *M. minutiflora,* which can attract parasitoids into the crop

(Khan *et al.*, 1997a), may therefore increase the likelihood of parasitism of borers in the crop environment (Conlong, 1997a).

Promising push and pull plants were evaluated for their possible effect on *X. stemmator*'s foraging behaviour and parasitism of *E. saccharina* (Conlong and Kasl, 2001). In olfactometer experiments, these parasitoid wasps oriented positively towards the following four grasses: *S. bicolor*, *Melinis repens (Willd.) Zizka* (Cyperales: Poaceae), and South African and Kenyan varieties of *M. minutiflora.* These four grass species also had a positive influence on parasitism of *E. saccharina* in cage trials (Kasl, 2004).

Barker (2008) performed a cost-benefit analysis in which it was shown that planting *M. minutiflora* as a repellent grass to reduce the *E. saccharina* infestation had an economic advantage to farmers when infestation was at economically damaging levels. Field trials indicated that interplanting *M. minutiflora* in sugarcane, at intervals of 20 rows, resulted in a reduction in *E. saccharina* populations of up to 50%, and a 57% reduction in stalk damage in fields with high populations of *E. saccharina*. The suggested method of planting *M. minutiflora* 0.5m away from the cane row adjacent to an irrigation drainage line and/or road provided an unexpected benefit in that it prevented encroachment of weeds into the sugarcane field from these more open areas (Barker *et al.*, 2006; Conlong and Campbell, 2010). Weed biomass was reduced by up to 79% and *M. minutiflora* did not have an effect on sugarcane growth parameters or yield (Barker, 2008). These outcomes supported the development of a habitat management system with a focus on *M. minutiflora*, as this grass was shown to reduce damage by *E. saccharina* (Kasl, 2004; Barker *et al.*, 2006), suppress weeds (Conlong and Campbell, 2010) and did not affect growth or yields of the crop (Barker *et al.*, 2006; Conlong and Campbell, 2010).

Recent research into the chemical ecology of the push-pull system showed that certain semiochemicals in the volatile profile of *M. minutiflora* significantly attracted larvae of *E. saccharina*, but repelled moths (Harraca *et al.*, 2011). These observations add to the complexity and challenge of developing a push-pull system for managing *E. saccharina.* Since stems of *M. minutiflora* are much thinner than the stems of *E. saccharina*'s usual host plants, it seems unlikely that larvae would be able to complete their development on this grass. It could however be used as a dead-end trap crop. This needs to be further investigated.

Eldana saccharina is one of the five most important borers of maize, especially in West Africa (Girling, 1978; Bosque-Pérez and Schulthess, 1998; Polaszek, 1998). Cochereau (1982) identified maize as a potential trap crop for *E. saccharina* infesting sugarcane in the Ivory Coast. With the advent of transgenic maize incorporating the insecticidal *Bacillus thuringiensis* (Bt) gene, the potential use of this plant as a trap for *E. saccharina* became more attractive (Keeping *et al.*, 2007). The advantage of using Bt maize rather than conventional maize is that it will act as a 'dead-end trap crop' as lepidopteran stem boring larvae feeding on it are killed upon ingestion of the Bt toxin. This means that the maize trap crop would not need to be destroyed. Keeping *et al.* (2007) found that Bt and non-Bt maize were significantly more attractive to egg-laying *E. saccharina* moths than sugarcane, with a preference for older maize plants with abundant dry leaf material. The third important finding from this research was that the Cry1Ab toxin in Bt maize killed *E. saccharina* larvae at all growth stages of the maize plant and that Bt maize would therefore be an ideal dead-end trap crop to 'pull' this pest out of the sugarcane (Keeping *et al.*, 2007).

A good knowledge base has improved the understanding of the relationships between various life stages of *E. saccharina,* its host plants and natural enemies (Conlong, 1990; Conlong, 2001; Mazodze and Conlong, 2003; Kasl, 2004; Assefa *et al.*, 2006; Smith *et al.*, 2006; Keeping *et al.*, 2007; Barker, 2008; Harraca *et al.*, 2011). This biological and ecological knowledge has been synthesized into a habitat management system called push-pull, as is illustrated in Figure 1.3 (Conlong and Rutherford, 2009; Rutherford and Conlong, 2010). Although the biology and ecology of *E. saccharina* and its host plants and parasitoids is still not fully understood, researchers involved in the development of this tool are confident that enough is known about the positive effects of push and pull plants to initiate implementation of this strategy at farm-level (Webster *et al.*, 2005; Conlong and Rutherford, 2009; Webster *et al.*, 2009; Rutherford and Conlong, 2010).

Efforts to begin introducing push-pull as part of an area-wide integrated pest management (AW-IPM) system on large-scale commercial sugarcane farms in the Midlands North area of KwaZulu-Natal were initiated during 2003 (Webster *et al.*, 2005; Webster *et al.*, 2009). The main focus of the programme in the Midlands North area has been the promotion of good crop management practices and the planting of sedges in wetlands to provide a habitat (a 'pull') for *E. saccharina*. Planting *M. minutiflora* as a 'push' plant in the contour banks between rows of sugarcane has also been encouraged (Webster *et al.*, 2005; Webster *et al.*, 2009), however this practice has not yet been adopted by many growers (Webster, pers. comm.).

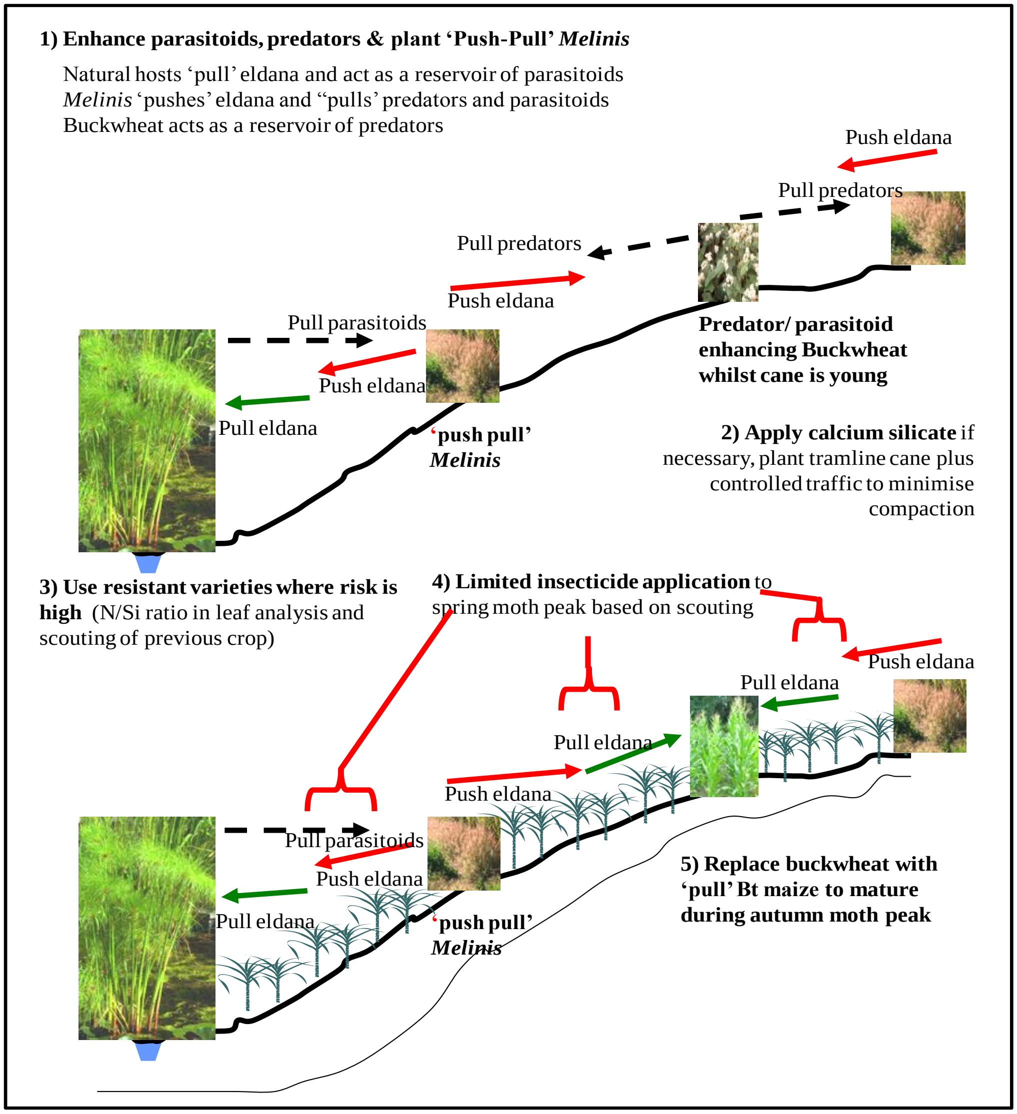


Figure 1.3. Diagram showing how push-pull could be implemented as part of an integrated pest management system in sugarcane (from Rutherford & Conlong 2010).

1.2 Facilitating the implementation of integrated pest management

1.2.1 The challenge of implementing IPM

Push-pull is being promoted as part of an AW-IPM system for control of *E. saccharina* in the South African sugar industry (SASRI, 2005; Webster *et al.*, 2005; Webster *et al.*, 2009; Rutherford and Conlong, 2010). A model for implementing push-pull, together with IPM, is needed by researchers and extension specialists at SASRI who are tasked with facilitating adoption of push-pull amongst sugarcane growers. Lessons learned by other practitioners of similar integrated and ecological pest management strategies can inform this model.

Tactics for facilitating the implementation of IPM by farmers have generally mirrored approaches to agricultural extension at the time. The transfer of technology (ToT) model (linear model of innovation), which also has some similarities to the diffusion of innovation model described by Rogers (1983), has been one of the most prevailing paradigms in extension of agricultural information, knowledge and technology in the last few decades (Chambers *et al.*, 1989; Norton *et al.*, 1999; Meir and Williamson, 2005; Peshin *et al.*, 2009b). This model has also been used in the agricultural extension programme at SASRI (Gillespie *et al.*, 2009b; SASRI, 2011). Inherent to this model are assumptions that researchers and scientists hold the key to knowledge and information which farmers need to improve their farming. Improved farming is usually measured as an increase in productivity, and according to the model, technology needs to be transferred from researchers to farmers. In this linear, top-down approach, extension workers are seen as the conduit by which knowledge or technology is transferred in a unidirectional manner from agricultural researchers to recipient farmers to help them (Kline and Rosenberg, 1986; cited in Leeuwis, 2004) (Figure 1.4). In this model, extension workers tell farmers about new technology and through this, the training and visit (T&V) method was popularised. The ToT model has however been widely criticised (Chambers *et al.*, 1989; Röling and de Jong, 1998; Leeuwis, 2004), particularly as it does not allow much scope for farmers to contribute to development of knowledge, especially for resource-poor farmers who have a greater need for self-sufficiency (van Huis and Meerman, 1997).

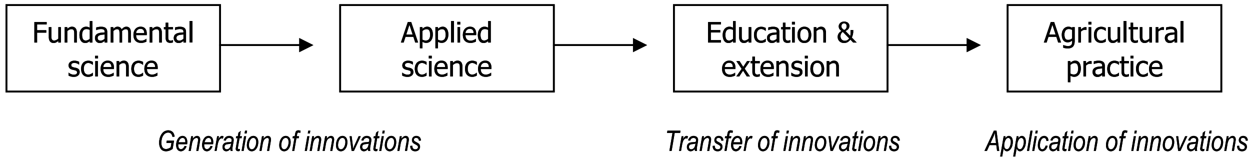


Figure 1.4. The linear model of innovation (from Leeuwis, 2004).

The ToT and diffusion of innovation models had some successes in the adoption of simple input technologies such as improved high-yielding varieties, fertilizers and other agro-chemicals which are typical of agricultural systems in most industrialized countries and also of the ‘Green Revolution’ of South-East Asia (Röling and van de Fliert, 1994). However, researchers and extensionists promoting IPM soon found this simple linear approach to be unsuitable for educating farmers about the more complex nature of IPM (van de Fliert, 1993; Castillo, 1998; Matteson, 2000; Peshin and Dhawan, 2009).

The recognition that linear ToT models of extension were not suitable for implementation of IPM lead to the development of numerous new extension models from the late 1980s onwards. Most of these attempted to take a more participatory approach to extension and implementation of agricultural research, and were informed by the work of development and social scientists, amongst others Chambers (1989) and Thompson and Scoones (1994), who emphasized the need to put the ‘farmer first’. Some of the more widely-cited approaches and methodologies which appeared during this time are Farmer Participatory Research (FPR) (Shepard *et al.*, 2009), Participatory Technology Development (PTD) (van Veldhuizen, 1997), Participatory Extension Approaches (PEA) (Hagmann *et al.*, 1999), and Farmer Field Schools (FFS) (Röling and van de Fliert, 1994; Röling and van de Fliert, 1998; Braun *et al.*, 2006; van den Berg and Jiggins, 2007). These models are drawn from a number of different countries, and most were tailored to suit specific attributes of local farming systems, however, some common themes can be identified throughout.

The first of these is participation, as can be seen from some of the acronyms. The Participatory Rural Appraisal (PRA) toolbox (Chambers, 1994) has been applicable in many different rural and agricultural development programmes, and has been incorporated into many of these newer extension methods. Participation here refers not only to active participation of the farmer, who becomes less of a client and more of an active role-player in ‘solving’ his or her agricultural problems, but also participation of multiple stakeholders (farmers, extension workers, researchers, policy-makers, local government officials and community members).

Experiential and social learning have also been recognised as a crucial part of successful ‘communication for rural innovation’ (Pretty, 1995; Röling and Jiggins, 1998; Meir and Williamson, 2005). The latter phrase has been suggested as a replacement for the term ‘extension’ which is loaded with connotations of the linear, top-down transfer of knowledge or technology (ToT) (Leeuwis, 2004). Experiential learning has been a cornerstone of the FFS programmes in South-East Asia, and its value in empowering farmers to better understand their agroecosystems and therefore make better decisions has been widely demonstrated (Röling and van de Fliert, 1994; Matteson, 2000; Ooi *et al.*, 2005). FFS has also been shown to be particularly beneficial to women farmers and farmers with poor education (Davis *et al.*, 2012). Empowering farmers makes them more resilient in times of change, and less reliable on external inputs for managing pest problems and other environmental challenges (Röling and Wagemakers, 1998). It is imperative for agricultural researchers, including entomologists developing and hoping to implement IPM programmes, to work more closely with farmers in a participatory way. This facilitates learning and innovation, and a better understanding of the constraints of farmers (van Huis and Meerman, 1997; Snapp *et al.*, 2003; Meir and Williamson, 2005).

Röling *et al.* (2004) made a strong case for undertaking what they termed ‘diagnostic studies’ to better understand farmers’ agricultural systems, in particular their production constraints, so as to effectively link farmers’ innovative capacity with the benefits of scientific research. They proposed diagnostic studies to involve farmers in development of improved agricultural technologies (Nederlof *et al*., 2004; Röling *et al*., 2004). An example of such a diagnostic study was conducted with cotton farmers in Ghana and Benin to determine their perception of cotton pests and their cotton pest management activities (Sinzogan *et al.*, 2004). In this study, researchers attempted to identify production constraints, both technical and socio-economic/organisational. Results of these investigations identified the need for discovery learning to increase farmers’ basic knowledge and skills with respect to pest biology and pest management, before an IPM system can be implemented (Sinzogan *et al.*, 2004). Peshin *et al.* (2009b) also emphasized the importance of designing IPM programmes with farmers, rather than for farmers, to take into consideration their needs, perceptions, resource constraints and objectives.

In a local example of such a study, Van den Berg (2012) and Van den Berg and van der Walt (2010) conducted a study in the Limpopo Province of South Africa to determine small-scale farmers’ constraints to maize production. They found socio-economic and political constraints to be limiting factors in adoption of production-improving technologies, and acknowledged that a more participatory approach was needed to fully understand agricultural systems of small-scale maize farmers in the Limpopo Province. Pretty (2003) analysed technical, social, institutional and political constraints to implementation of sustainable agricultural practices worldwide, and similarly found that political conditions were likely the most limiting of these constraints for the successful implementation of improved practices. Van Huis (2009) and Nederlof *et al.* (2007) also indicated that institutional development needs should be addressed as much as technological improvement, in particular for smallholder food production and to improve adoption rates of IPM in sub-Saharan Africa. Van Huis (2009) also noted that farmers’ lack of access to external inputs and finance are often blamed for poor IPM adoption rates. This is a case of putting the horse before the cart: shouldn’t IPM be adapted to suit farmers’ conditions and constraints? According to Van Huis (2009: 441) this “shows the paradigm problem in which the constraints of the farmer are not taken as a starting point but as a constraint”.

The findings of Van den Berg (2012) and Van den Berg and van der Walt (2010) have interesting parallels with the situation of small-scale sugarcane growers in KwaZulu-Natal, South Africa. Socio-economic and organisational constraints for these farmers have also been identified as a high priority to be addressed by relevant support structures within the sugar industry (Mahlangu and Lewis, 2008; Armitage *et al.*, 2009). The unsuccessful implementation of improved sugarcane production practices in the Amatikulu catchment area was attributed to socio-economic, organisational and institutional constraints beyond the field and farm level (Mahlangu and Lewis, 2008). Social research into farmers' perceptions of their constraints and an understanding of their farming practices, for example a diagnostic study as recommended by Röling *et al.* (2004), might have increased the likelihood of adoption of the best management practices (BMPs) promoted by SASRI in the project reported by Mahlangu and Lewis (2008). One needs to bear this case study in mind when developing a model for the implementation of push-pull, as this also represents a type of BMP for sugarcane farmers.

1.2.2 Successful implementation of push-pull in Kenya

Determining farmers' perceptions of pests and pest management techniques has been found to play an important role in the successful implementation of pest management technologies, because it allows for a better understanding of farmers' decision-making behaviour (Heong and Escalada, 1999; Ebenebe *et al.*, 2001; Leeuwis, 2004; Meir and Williamson, 2005). To better appreciate the motivations for small-scale maize farmers adopting (or not adopting) the push-pull strategy, Khan *et al.* (2008a) evaluated farmers' perceptions of push-pull, as well as their sources of information on push-pull and their motivations for adoption. The study showed that farmers' interaction with any of the extension/dissemination methods used for push-pull increased the likelihood of adoption. Serious production constraints imposed by the parasitic weed, *S. hermonthica*, as well as stem borers, motivated farmers to adopt push-pull (Khan *et al.*, 2008a). It is not surprising that farmers are more likely to adopt agricultural technology which can improve production, and which is compatible with their own farming system. If farmers experience these benefits on their own farms, then the importance of 'early adopters' in facilitating adoption to others becomes clear (Feder and Savastano, 2006). Early adopters were found to be the primary source of information for farmers wishing to learn more about, and possibly adopt, push-pull in many regions of Kenya (Khan *et al.*, 2008a).

The main pathways of technology dissemination employed by agricultural researchers and extension staff in the push-pull project in Kenya were field days (Amudavi *et al.*, 2009a), farmer teachers (Amudavi *et al.*, 2009b), mass media, public meetings (barazas), printed materials and farmer field schools (ICIPE, 2007; Khan *et al.*, 2011; Murage *et al.*, 2011a). Early on in the development of the push-pull strategy, farmers were included in the process by moving trials from agricultural research stations to farms where they were initially managed by scientists but then handed over to farmers to manage (Khan *et al.*, 2008b). To optimise the dissemination strategy for push-pull, Murage *et al.* (2011) performed an analysis to determine farmers' preferences for the various dissemination pathways used. It was found that the preferences of farmers with different educational backgrounds, farm sizes and belonging to different organisational structures differed, and that technology dissemination should be tailored to suit the unique situation of farmers. For example, younger more educated farmers preferred printed materials, whereas less educated farmers preferred field days and farmers belonging to a farmer organisation preferred farmer field schools (Murage *et al.*, 2011a).

In a review of push-pull strategies used in IPM, Cook *et al*. (2007) report that successful implementation of push-pull strategies, other than the exampled discussed above for Kenya, was rare. Of the twenty case studies they presented, only two have successfully been used in practice. In a discussion on implementation of conservation biological control, which includes knowledge intensive approaches to pest management such as push-pull, Ehler (1998) argued that the reason for poor adoption of ecologically-based control measures for pest management, was that these methods were not always economically viable and did not necessarily integrate effortlessly with current farming practices.

It is precisely because Khan *et al.* (2008c) addressed these two important constraints to adoption, that implementation of push-pull for management of cereal stem borers in Kenya was successful. Push-pull was shown to be economically viable (Khan *et al.*, 2008c) and integrated well with small-scale maize farmers' practices in East Africa (Khan *et al.*, 2008b; Khan *et al.*, 2011). This is what Peshin *et al.* (2009b) term a 'good fit' between IPM practices and the farm situation. These are however not the only ingredients needed for successful adoption of agricultural technology. As indicated above, successful adoption is largely ascribed to a multi-disciplinary, multi-stakeholder approach in which farmers actively participate in development of technology, and their learning is facilitated in an empowering manner.

Critics of the ToT extension model might question the approach taken by the ICIPE team in dissemination of technology based on the discourse used by researchers. This discourse typifies the top-down approach criticised by some social scientists, as described in 1.2.1 above (Chambers *et al.*, 1989; Röling, 2004). Words like 'dissemination', 'adoption of technology' and 'transfer of knowledge' occur frequently in the literature of the push-pull project. However, one must look beyond the researchers' language, to their activities and achievements. Their language does not match that of Röling (2004) and Leeuwis (2004) who suggested moving away from the term 'extension' to 'communication for rural innovation', but the way in which they worked with local communities, organisations and other research institutes in a multi-stakeholder collaboration ensured the success of their project (Amudavi *et al.*, 2007; Khan *et al.*, 2011). Their participatory, farmer-first approach to disseminating the knowledge intensive, but highly suitable, push-pull strategy has been successful. The researchers carried out trials together with farmers (Khan *et al.*, 2008b), engaged the farmers to teach other farmers in farmer field schools and then provided the farmer teachers with opportunities to train new farmer teachers (Amudavi *et al.*, 2009b). This ensured high rates of sustainable technology adoption (Amudavi *et al.*, 2007; Khan *et al.*, 2011).

1.2.3 A working model for implementing push-pull with sugarcane farmers

In developing a working model to facilitate the implementation of push-pull as part of an IPM approach for controlling *E. saccharina* on sugarcane, the success of the Kenyan push-pull programme, together with the international body of knowledge on suitable extension and IPM implementation approaches, will be used as a guide. Details of the working model are described in the aims and objectives in section 1.3 below.

1.3 Aims, objectives and thesis structure

1.3.1 Aims and objectives

The main aim of this study is to facilitate the implementation of push-pull for the control of *E. saccharina* on sugarcane in the Midlands North region of KwaZulu-Natal, South Africa.

This will be achieved through the development of a working model for implementation of push-pull as part of IPM for the sugar industry. The working model has the following objectives:

- to determine farmers' production constraints and their knowledge and perceptions of *E. saccharina*, push-pull and IPM (for both large- and small-scale growers)
- to evaluate current adoption levels of push-pull among large-scale growers and to explore the drivers and barriers to adoption
- to set up model farms. On these model farms, the farm-level efficacy of push-pull for control of *E. saccharina* will be determined, hands-on experiential learning opportunities will be

provided to farmers and push-pull will be adapted to suit the management activities of sugarcane farmers

- to contribute to the understanding of the host plant-stem borer-parasitoid complex in sugarcane agroecosystems by conducting surveys in wetlands on model farms.

1.3.2 Thesis structure

Chapter 1 is a general introduction and literature review of push-pull, *Eldana saccharina* and various extension models for the implementation of push-pull and integrated pest management. The project aims and objectives are defined in this first chapter. In Chapter 2 and 3, small- and large-scale farmers' production constraints, knowledge and perceptions of *E. saccharina* and pest management are explored as a means of facilitating implementation of push-pull. In Chapter 4, the current adoption of push-pull by large-scale growers in the Midlands North region is evaluated and reasons for adoption or non-adoption are explored using a novel methodology: exploratory network analysis. Chapter 5 presents the results of on-farm trials to determine the efficacy of push-pull by measuring stem borer infestation and damage in push-pull treatment and control areas on model farms. In Chapter 6 the indigenous stem borer complex in wetlands on model farms is described, with a discussion on what implications this may have for biosecurity and management of stem borers in the sugarcane agroecosystem. The results of wetland health assessments are presented and recommendations are made to farmers on how best to manage wetlands on their farms for improved habitat management of *E. saccharina*. In Chapter 7, general conclusions are drawn about the relevance of the findings of this study and recommendations are made for further research and implementation of push-pull in other sugarcane production regions of South Africa.