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Assessing the Status of "Push-Pull" Technology in Worldwide Agriculture and Forestry

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ABSTRACT

"Push – pull" insect pest management refers to the simultaneous use of intercrops as pest repellents and attractants to respectively "push" pests away from a protected crop, and "pull" them into a trap crop where they may be controlled, preferably using biological methods. Ideally, the effects are synergistic. Repellents and attractants may include natural or synthetic plant chemicals or products. The authors tabulated primary scientific literature on research and applications of push-pull technology (PPT) worldwide in agriculture and forestry. The East African work on the maize-stemborer-Desmodium-Napier grass system remains the definitive success story. There are several unconnected research efforts in North America and Asia, and very few examples in South America and Europe. The reasons for the minimal and uneven success with PPT are unclear. Plants that are attractive or repellent to insect pests are found throughout the world. Therefore, candidates for use as push or pull plants should not limit the applicability of PPT to selected geographical regions. Moreover, PPT tools such as synthetic plant volatiles and attractive or repellent lighting should be effective anywhere. Social factors may be essential to successful PPT implementation. An effective system of knowledge transfer from researcher to the farmer must be available. Successful PPT is more likely when farmers have a tradition of companion cropping. Multiple cropping systems have been used historically throughout the world, although its practice declined significantly in industrialized countries with the advent of modern agriculture. Multiple cropping is common throughout Asia, Africa and South America, and is typical in many resource-poor countries. Intensive monitoring and decision-making will be critical, thereby requiring considerable investments in research and labor. Operational costs will be higher than conventional pest management and more variable efficacy must be tolerable. Many of these requirements for PPT will be inapplicable in the intensive agricultural systems of more developed countries but may have some use in small organic farms or greenhouse settings of industrialized countries. PPT has proven it can be economically viable. The technology may be underexploited in parts of Asia and South America. It is possible that the main hindrance to more widespread application in many parts of the world may be more related to a lack of technical services and/or dependency on chemicals that is difficult to overcome.

Additional index words: attractants, repellents, trap crops, natural plant chemicals, insect pests

INTRODUCTION

"Push – pull" insect pest management refers to the simultaneous use of intercrops as pest repellents and attractants to respectively "push" pests away from a protected crop, and "pull" them into a trap crop where they may be controlled, preferably using biological methods. Ideally, the effects are synergistic. Repellents and attractants used in push-pull may include natural or synthetic plant chemicals or other products in addition to crops. The term has also been used wherein the attractants are applied to natural enemies and not pests (e.g., Xu et al. 2018). Although the term has also been applied to natural enemies, herein, we consider only its use for pests.

The foundations of push-pull technology (PPT) were laid over 30 years ago in Australia by Pyke et al. (1987) who studied neem and antifeedants as push factors with pigeonpea (*Cajanus cajan*) and maize (*Zea mays*) as pull against *Helicoverpa (*= formerly *Heliothis) armigera* (Hubner) (Lepidoptera: Noctuidae) in cotton. (*Gossypium* spp.) Almost simultaneously, the concept was independently developed by Miller and Cowles (1990) using ovipositional deterrents cinnamaldehyde and phenethanol (push) and cull onions (pull) against the onion maggot (*Delia antiqua* (Meigen) (Diptera: Anthomyiidae)) in onion fields in Michigan. They called the technology “stimulo-deterrent diversion”. Here we will adopt the more widely-used term push-pull.

Since its origin, a substantial body of literature has developed on the worldwide use of PPT and the biological mechanisms involved in its implementation (e.g., Pickett et al. 1997, 2014, Cook et al. 2007, Hassanali et al. 2008, Khan et al. 2014a, Eigenbrode et al. 2016, www.push-pull.net). The singular success story of PPT resulted from a collaborative project at the International Centre of Insect Physiology and Ecology (ICIPE) in Kenya, with Rothamsted Research in the United Kingdom, the Kenyan Agricultural Research Institute (KARI), and other organizations (Khan et al. 2011). In this PPT system, maize and sorghum (*Sorghum bicolor*) crops are protected against stem borers, primarily *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae), and *Chilo partellus* (Swinhoe) (Lepidoptera: Crambidae) using molasses grass (*Melinis minutiflora*) and *Desmodium* spp. (Leguminosae) forage legumes as the push factor, and Napier grass (*Pennisetum purpureum* Schumach) and Sudan grass (*Sorghum sudanensis*) planted on the borders as the pull factor (Khan et al. 2000, 2011, 2014a, b; Table 1).

The ICIPE PPT program has proven beneficial in several ways. The companion crops provide animal fodder, and Desmodium improves soil fertility through nitrogen fixation, which also helps to control *Striga* spp. weeds. Recent studies indicate that PPT also induces changes in soil chemistry enhancing resistance to insect pests (Mutyambai et al. 2019). Economic analysis has shown that the ICIPE-PPT has considerable potential to increase economic surplus and reduce poverty in Kenya (Kassie et al. 2018). The ICIPE-PPT has resulted in a benefit to cost ratio of 2.5 and the number of subscribing farmers increased from a few dozen to more than 80,000 within a period of 15 years (Winter et al. 2014). The program aimed to reach 1 million farm households by 2020 (Khan et al. 2014b). Adoption of PPT on 250 farms in Kenya, Uganda and Tanzania resulted in 86.7% reduction in fall armyworm (*Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae)) plant damage and slight (2.7%) increase in grain yield compared to maize monocropping (De Groote et al. 2020).

STATUS OF PUSH–PULL ARGRICULTURE

Cook et al. (2007) summarized the state of PPT (see Suppl. Table 1) and concluded that successful application was largely limited to Kenya and nearby parts of East Africa, and that the studies were the products of the same groups of workers. We attempt to update Cook et al. (2007) and Eigenbrode et al. (2016) with respect to agricultural and forestry research and use of PPT worldwide. Table 1 shows results of searching primary scientific literature on research and applications of PPT worldwide, according to continent and country. We excluded other areas of PPT research, such as in medical entomology or non-entomological research. We cite only those studies conducted within a PPT framework, and excluded research exclusively on repellents or attractants. We selected works with a component of (preferably) field experimentation and excluded those that simply proposed or speculated on the applicability of PPT to a given cropping system.

While by no means comprehensive, we believe Table 1 adequately reflects the worldwide status of PPT research in agriculture and forestry. The East African work on the maize-stemborer-Desmodium-Napier grass system remains the definitive success story. There are several unconnected research efforts in North America and Asia and few in South America and Europe. Applied PPT may be underreported in the predominantly Western scientific journals. It seems that despite the work and success of research teams at ICIPE-PPT the technology remains underutilized. As Eigenbrode et al. (2016) noted, the Kenyan success story will be difficult to replicate elsewhere.

WHAT IS NEEDED FOR PUSH–PULL TO BE SUCCESSFUL ELSEWHERE?

Plants that are attractant and repellent to insect pests are found throughout the world (Metcalf and Kogan 1987, Maia and Moore 2011). Therefore, candidate push or pull plant species should be plentiful and not limit the applicability of PPT to selected geographical regions (e.g. East Africa). Furthermore, PPT can be based on synthetic plant volatiles and other artificial cues such as attractant or repellent lighting (Pawson and Watt, 2009). We believe it is unlikely that insect – plant interactions alone will limit the applicability of PPT to a given cropping system.

Kebede et al. (2018) suggest that PPT must be designed and evaluated with consideration of the surrounding landscape. They found that in field experiments using the maize-stemborer-Desmodium-Napier grass system in simple landscapes, stemborers located the host maize, regardless of the presence of Desmodium or Napier grass. In complex landscapes, the push-pull effects were likely masked (Kebede et al. 2018). More research of this nature would be useful. These authors concluded that success of PPT might be facilitated in landscapes of intermediate ecological complexity.

In addition to biological factors, several socio-economic requisites are needed for successful PPT implementation. Because PPT management requires a thorough understanding of the ecological interactions involved in the plant-herbivore-natural enemy communities, intensive monitoring and decision-making will be critical. Considerable investments in research and labor are necessary (Cook et al. 2007). Operational costs will be higher than conventional pest management and more variable efficacy must be tolerable.
Essential to successful PPT will be the availability of an effective system of knowledge transfer from researcher to the farmer (Hailu et al. 2017). Technology dissemination methods employed by ICIPE included field days, farmer teachers, mass media, public meetings, printed materials and farmer field schools (Khan et al. 2008a, 2008b). Also instrumental was the support of national agricultural research institutes and extension systems, institutions of higher learning, non-governmental organizations (NGOs), donors and other national programs (Khan et al. 2011).

Successful implementation of PPT is more likely when the farmers have a tradition of companion cropping (Khan et al. 2011). Multiple cropping systems have been used historically throughout the world, although its practice declined significantly in industrialized countries with the advent of modern agriculture. The worldwide use of multiple cropping appears to decline with temperature and rainfall (Anders et al. 1996). Therefore, the practice is common throughout Asia, Africa and South America (Beets 2018), and is typical in many resource-poor countries (Khan et al. 2011).

Many of these requirements for PPT will be inapplicable in the intensive agricultural systems of developed countries but may have some use in small organic farms or greenhouse settings of industrialized countries. Because PPT has proven it can be economically viable (Chepchirchir et al. 2018), we believe the technology may be underexploited in parts of Asia and South America. It is possible that the main hindrance to more widespread application in many parts of the world may be more related to a lack of technical services and/or dependency on chemicals that is difficult to overcome.

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Table 1. Worldwide use of push-pull technology in agriculture and forestry

Continent	Country	Crop	Pest	Push	Pull	Reference
Africa	Kenya	maize, sorghum	Stem borers: *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae), *Chilo partellus* (Swinhoe) (Lepidoptera: Crambidae)	molasses grass (*Melinis minutiflora*), *Desmodium* spp. (Leguminosae)	Napier grass (*Pennisetum purpureum* Schumach), Sudan grass (*Sorghum sudanensis*)	Khan et al. (2000)
	Kenya	maize	*Busseola fusca*, *Chilo partellus*	*Desmodium* spp.	Napier grass	De Groote et al. (2010a,b), Hassanali et al. (2008), Vanlauwe et al. (2008a, b), Khan et al. (2008a, b, 2009, 2010, 2011, 2013, 2014a, b, 2016), Khan and Pickett (2001, 2004), Midega et al. (2006, 2009), Mutyambai et al. (2019), Ndayisaba et al. (2022), D'Annolfo et al. (2021)
	Ethiopia	maize	*Busseola fusca*, *Chilo partellus*	Desmodium	Napier grass	Belay and Foster (2010), Kebede et al. (2018)

	Ethiopia	maize	*Busseola fusca*, *Chilo partellus*	Desmodium	Brachiaria grass	Kumela et al. (2019)
	Ethiopia	maize, sorghum	*Busseola fusca*, *Chilo partellus*	Desmodium	Napier grass	Araya et al. (2015)
	Malawi	maize	stemborers	Desmodium	Napier, Brachiaria grass	Niassy et al. (2022)
	Uganda	maize	*Busseola fusca*, *Chilo partellus*	Desmodium	Napier grass	Chepchirchir et al. (2017)
	South Africa	sugarcane	*Eldana saccharina* Walker (Lepidoptera: Pyralidae)	*Melinis minutiflora* Beauv.	Indigenous host plants, Bt-maize	Conlong and Rutherford (2009), Harraca et al. (2011), Conlong et al. (2016), Cockburn et al. (2012, 2014)
	South Africa	maize	spotted maize beetle, *Astylus atromaculatus* Blanchard (Coleoptera: Melyridae)	Desmodium	Napier grass	Midega et al. (2007)
	Uganda	maize	fall armyworm (*Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae))	Desmodium	Napier grass	Hailu et al. (2018)
North America	Canada	lodgepole pines (*Pinus contorta*)	mountain pine beetle (*Dendroctonus ponderosae* (Hopkins) (Coleoptera: Curculionidae))	verbenone (antiaggregation pheromone)	Non host volatiles	Borden et al. (2003, 2006)
	United States (New York)	red raspberry	*Drosophila suzukii* Matsumura (Diptera: Drosophilidae)	1-octen-3-ol	visually and chemically attractive mass trapping device	Wallingford et al. (2018)

	US (Ohio, Virginia, Mississippi)	various wooded habitiats	ambrosia beetles (*Xylosandrus* spp.) (Coleoptera: Curculionidae)	verbenone	ethanol lures	Werle et al. (2018)
	US (Florida)	bell peppers	*Frankliniella bispinosa* (Morgan) (Thysanoptera: Thripidae)	(UV)-reflective mulch, kaolin	sunflower	Tyler-Julian et al. (2014)
	US (Florida)	tomato	western flower thrips (*Frankliniella occidentalis* Pergande)	(UV)-reflective mulch, kaolin	*Bidens alba* (L.)	Tyler-Julian et al. (2015, 2018)
	US (Maine, greenhouse)	Potato	Colorado potato beetle (*Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae)	Natural / synthetic potato volatiles	Natural / synthetic potato volatiles	Dickens and Alford (2004), Martel et al. (2005)
	US (Oregon)	Douglas fir	Douglas fir beetle (*Dendroctonus pseudotsugae* Hopkins (Coleoptera: Curculionidae))	Antiagregation pheromones	aggregation pheromones	Ross and Daterman (1994)
	US (Michigan)	onion	Onion maggot (*Delia antiqua* (Meigen) (Diptera: Anthomyiidae)	Cinnamaldehyde, phenethanol	Cull onions	Cowles and Miller (1992), Miller and Cowles (1990)
	US (Florida)	squash, cabbage, broccoli, collards, cantaloupe	*Bemisia argentifolii* Bellows & Perring (=*B. tabaci*) (Hemiptera: Aleyrodidae)	giant red mustard (*Brassica juncea* (L.), arugula (*Eruca sativa*), extracts	Squash cantaloupe cis-3-hexenyl acetate	Legaspi (2010), Legaspi and Simmons (2012), Legaspi et al. (2016), unpublished data
Europe	France	broccoli	*Delia radicum* L.	Synthetic volatile organic compounds	Chinese cabbage (*Brassica rapa* L.)	Lamy et al. (2017)
	France	broccoli	*Delia radicum*	dimethyl disulfide	Z-3-hexenyl-acetate	Lamy et al. (2018)

Asia	New Zealand	pasture field	*Thrips tabaci* (Lindeman) (Thysanoptera: Thripidae)	four plant essential oils	ethyl iso-nicotinate	van Tol et al. (2007)
	China	Tea	Tea green leafhopper, *Empoasca flavescens* F.	*Lavandula augustifolia* extract	*Flemingia macrophylla* extract	Han et al. (2020)
	Taiwan	radish	striped flea beetle (*Phyllotreta striolata* F. (Coleoptera: Chrysomelidae)	tomato	winter rape	Srinivasan et al. (2017)
	India	cotton	Cotton bollworm (*Helicoverpa armigera*) (Hubner) (Lepidoptera: Noctuidae)	Neem seed kernel extract	Okra, pigeonpea	Duraimurugan and Regupathy (2005a, b, c)
	New Zealand	*Pinus radiata* forest	Wood boring beetle *(Arhopalus ferus* (Mulsant) (Coleoptera: Cerambycidae)	'push' lights	UV 'pull' traps, 'pull' lighting	Pawson and Watt (2009)
	South Korea	Chinese cabbage	diamondback moth (*Plutella xylostella* (L.) (Lepidoptera: Plutellidae)), striped flea beetle (*Phyllotreta striolata* (F.) (Coleoptera: Chrysomelidae)), aphids, brown-winged stink bug (*Nezara antennata* Scott (Hemiptera: Pentatomidae)), cabbage stink bug (*Eurydema rugosa* Motschulsky (Pentatomidae))	Attractant/repellent plants (marigold, rye, Chinese chive, lettuce, chicory, Nongwoo-chicory, crown daisy, Treviso, green leaf mustard, red leaf mustard)		Kim et al. (2013)
South America	Argentina	forestry plantations	Leaf-cutting ants *(Acromyrmex ambiguus* Emery (Hymenoptera: Formicidae))	Farnesol	orange fruit (pulp and peel)	Perri et al. (2017, 2021)
Australia and Oceania	Australia	Cotton	*H. armigera*	Neem, antifeedant	Pigeonpea, maize	Pyke et al. (1987)

	Australia	Tomato	fruit flies (*Bactrocera tryoni* (Froggatt) Diptera: Tephritidae)	oil emulsion spray	protein bait spray	Meats et al. (2012)

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