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REVIEW

Maximizing farm-level uptake and diffusion of biological control innovations in today's digital era

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Abstract When anthropologists interviewed Honduran and Nepali smallholders in the mid-1990s, they were told that "Insects are a terrible mistake in God's creation" and "There's nothing that kills them, except for insecticides". Even growers who maintained a close bond with nature were either entirely unaware of natural pest control, or expressed doubt about the actual value of these services on their farm. Farmers' knowledge, beliefs and attitudes towards pests and natural enemies are of paramount importance to the practice of biological control, but are all too often disregarded. In this study, we conduct a retrospective analysis of the extent to which social science facets have been incorporated into biological control research over the past 25 years. Next, we critically examine various biological control forms, concepts and technologies using a 'diffusion of innovations' framework, and identify elements that hamper their diffusion and farm-level uptake. Lastly, we introduce effective observation-based learning strategies, such as farmer field schools to promote biological control, and list how those participatory approaches can be further enriched with information and communication technologies (ICT). Although biological control scientists have made substantial technological progress and generate nearly 1000 papers annually, only a fraction (1.4%) of those address social science or technology transfer aspects. To ease obstacles to enhanced farmer learning about biological control, we describe ways to communicate biological control concepts and technologies for four divergent agricultural knowledge systems (as identified within a matrix built around 'cultural importance' and 'ease of observation'). Furthermore, we describe how biological control innovations suffer a number of notable shortcomings that hamper their farm-level adoption and subsequent diffusion, and point at ways to remediate those by tactical communication campaigns or customized, (ICT-based) adult education programs. Amongst others, we outline how video, smart phones, or tablets can be used to convey key ecological concepts and biocontrol technologies, and facilitate social learning. In today's digital era, cross-disciplinary science and deliberate multi-stakeholder engagement will provide biocontrol advocates the necessary means to bolster farmer adoption rates,

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counter-act surging insecticide use, and restore public trust in one of nature's prime services.

Keywords Socio-ecological systems · Crop protection · IPM · Information diffusion · Conservation biological control · Rural sociology · Ecological intensification

Introduction

In 1992, Keith Andrews and colleagues at the Zamorano Panamerican School of Agriculture in Honduras signaled that biological control uptake was hampered by a limited two-way interaction between scientists and farmers (Andrews et al. 1992). Drawing upon their extensive expertise working with smallholder farmers in Central America, these expat scientists recognized that socio-cultural facets of integrated pest management (IPM) were routinely overlooked and called for more emphasis on social science research in the promotion of biological control. Concurrently, at the other side of the globe, similar views were expressed by e.g., Roling and van de Fliert (1994), for the particular case of biological control in Asia's expansive rice crops. Now, 25 years after these assertions, we take the pulse of biological control globally, assess trends in its promotion and adoption, and venture into the field of (digital) social research to gauge current scientific interest in this discipline. Furthermore, we identify key shortcomings of biological control technologies from a 'diffusion of innovations' perspective (Rogers 1962), and point at ways to more effectively transfer key concepts and practices amongst a variety of end-users, including farmers, private sector actors and the general public. Amongst others, we examine the different factors that shape farmers' agro-ecological knowledge, and provide recommendations on how to ease particular obstacles in farmer learning on biological control. We conclude our paper with a comprehensive overview of today's information and communication technologies (ICTs) and their potential value in biological control education and social learning.

Since the early 1900s, when University of California at Riverside, USA scientists famously minted the term 'biological control', the tactical introduction, release and in-field conservation of arthropod natural enemies has resulted in effective control of multiple endemic and exotic pests, and has provided massive economic, environmental and societal benefits (e.g., van Lenteren et al. 2006; van Driesche et al. 2010; De Clercq et al. 2011). However, since the early days of 'unrestrained enthusiasm' and 'ladybird fantasies' (Warner et al. 2011), lots has changed. Although host-specific natural enemies carried out precision-strikes against cassava mealybugs and mites, averted wide-spread famine in sub-Saharan Africa, and led to a resurge of the 'biocontrol bonanza' (IITA 1996), certain momentum has been lost over the past two decades. Overly stringent regulations for environmental risk assessment of exotic agents, shifting scientific interests and dwindling public attention have led to the abolition of biological control in core curricula of several academic institutions, and have hampered efforts to implement biocontrol globally. The future may hold lucrative opportunities under the current European legislative climate (Lamichhane et al. 2017), but those have to be examined strategically. These latter trends notwithstanding, biological control does find itself at a cross-roads, and careful analysis, from a range of different angles, is warranted to diagnose key deficiencies, identify roadblocks and point the way forward for this most valuable practice.

Although global adoption rates of biological control are poorly documented (Chandler et al. 2011), notable achievements continue to be made though at a 'frustratingly' slow pace. Adoption rates of biological control vary considerably between its three main forms: classical (introduction), augmentation and conservation (e.g., Eilenberg et al. 2001). These different forms of biological control have experienced varying levels of 'success', as measured by the extent to which farmers throughout the world rely upon them for pest management (Gurr et al. 2000). Through classical biological control programs, >2000 species have been introduced, leading to permanent suppression of more than 165 arthropod pests. In different geographies and (agro-)ecosystems, this has resulted in substantial economic benefits, which continue to accumulate annually and are regularly taken for granted (e.g., Zeddies et al. 2001; van Driesche et al. 2010). Although a number of classical biological control programs have been scaled down in recent years, multiple initiatives remain in steady progress and continue to yield impressive results (e.g., Myrick et al. 2014). The practice of augmentation biological control has become a full-blown market-driven undertaking, gained a firm foothold in greenhouse cultivation within Europe and North America, and is regularly used in open-field horticulture in different parts of Europe (van Lenteren 2000). However, in other parts of the world and in field crops, commercial augmentative biological control has largely failed to take root (Bailey et al. 2009; van Lenteren 2012). One notable exception is the use of mass-produced *Trichogramma* spp. and *Cotesia flavipes* wasps on Brazil's 9 million ha sugarcane crop, or state-endorsed biological control programs in countries such as Cuba and Mexico (Rosset 1997; Parra 2014). Lastly, despite being the world's oldest form of pest control, the practice of conservation biological control has so far met with feeble rates of adoption globally (Cullen et al. 2008; Wyckhuys et al. 2013). Although naturally-occurring biota provide pest control services at a value of $4.5–17 billion annually in the USA (Losey and Vaughan 2006), most growers are entirely unaware of the intricate ecological processes that occur on their farms, and lag in using approaches to encourage natural enemy colonization, in-field abundance or pest control action. Push–pull systems may be a noteworthy exception though, as those tactics have been widely adopted by African subsistence farmers to control key pests on sorghum and maize (Cook et al. 2007).

The biggest stumbling block for conservation biological control is that 'from the viewpoint of an individual decision maker', it remains a 'most problematic investment' (Perkins and Garcia 1999). While Andrews et al. (1992) already identified close farmer involvement and informed technology delivery programs as essential to the up-scaling of biological control techniques, these same constraints continue to be listed as key impediments by Gurr et al. (2000), Bale et al. (2008), Cullen et al. (2008) or Waterfield and Zilberman (2012). More so, renewed calls are being made for an in-depth characterization of end-user knowledge, attitudes and perceptions, and a subsequent deployment of comprehensive educational campaigns to promote biological control (e.g., Naranjo et al. 2015). In light of the above, we conduct a critical assessment of the extent to which social science perspectives have been incorporated into biological control research over the past 25 years. We examine whether biocontrol practitioners have effectively employed social science approaches, learned from experiences in the 1990s and embarked in cross-disciplinary initiatives, or whether those disciplines continue to be overlooked and 'social science' is simply referred to as a factor to blame farmers' lagging adoption of specific technologies.

As a first step in our assessment, we ran an ISI Web of Knowledge search for arthropod biological control studies that deliberately took into account social science aspects. Covering 12,000 journals, our ISI Web of Knowledge search was restricted to abstracts of papers that were published over the time period of 1990 up till November 2016. Studies that covered IPM without explicitly mentioning biological control were not taken into consideration. A core set of papers on insect biological control was consolidated by using the search terms (("biological control" OR "natural enem*") AND ("insect*" OR "arthropod")). These search terms were defined by the authors. Within this set, we ran the following additional queries:

- (("farmer" OR "stakeholder" OR "public") NOT "public health")), for studies that make reference to end-users;
- (("gender" OR "women" OR "woman")), for studies that make reference to gender-aspects (solely of target adopters, and not insects);
- (("intergeneration*" OR "youth" OR ("young" AND "age") OR "children")), for studies that take into account age of target adopters, or include youngsters;
- (("knowledge" OR "innovation" OR "information") AND ("diffusion" OR "transfer" OR "dissemination" OR "training")), for manuscripts that allude to knowledge transfer;

For each of the above queries, abstracts of the resulting papers were screened and irrelevant studies were omitted from the analysis. Over the 27-year time period, a total of 11,732 manuscripts were found. The number of biological control publications gradually increased from 38 per year in 1990 to 720–886 per year in recent years (Fig. 1). Within this extensive literature base, a total of 161 studies (or 1.4%) were found in which reference was made to farmers, stakeholders, value-chain actors or the general public. Onstad and Knolhoff (2009) made similar findings, when revising economic entomology papers for the level of attention to economic aspects of pest control. Even fewer papers (i.e., a total of 28, over the 27-year time period) covered aspects such as knowledge transfer and technology

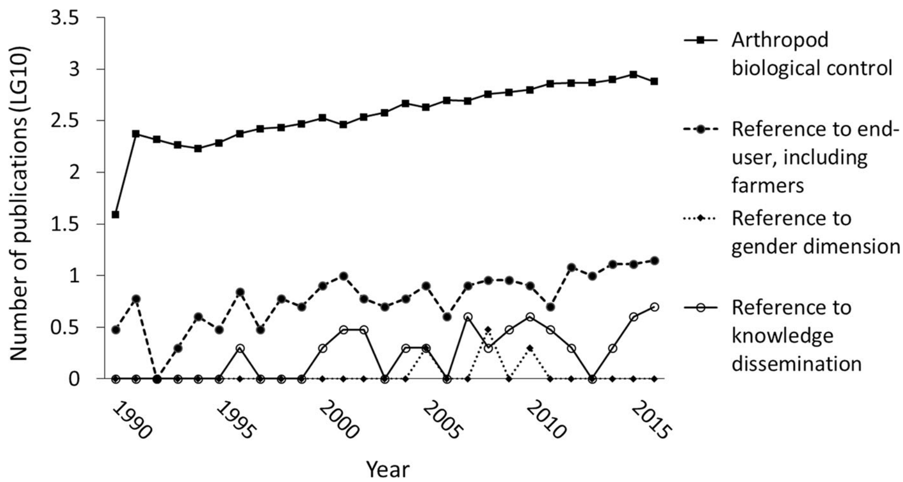

Fig. 1 Results from an ISI Web of Knowledge search for arthropod biological control studies that have taken into consideration social science aspects, over a 1990–2016 time period. Data are plotted on a log10 scale. For a particular year, the number of publications on insect biological control is contrasted against the number of papers that take into account end-users (including the general public and farmers), cover gender aspects, or make mention of knowledge dissemination

diffusion. As little as four publications made reference to gender aspects, and either mentioned women or female adopters in the abstract. Lastly, no studies were found in which specific attention was paid to youth or young farmers. Among the 32 manuscripts that either covered technology transfer or gender aspects, 35% originated in Asia and 25% were conducted in the Americas. Only 9% of these studies were from Europe, and two studies had a global coverage. For country-specific patterns, China represented the highest number ($n = 4$) of studies, while Vietnam and the USA each represented three studies.

Our literature search thus revealed that biological control advocates thus continue to pay scant attention to social sciences, and largely omit farmer decision-making, technology diffusion or communication facets. Given the high level of farmer heterogeneity and the context-dependent nature of biological control (e.g., Rebaudo and Dangles 2013), one is left to wonder whether an average of 6.0 manuscripts per year with some social science 'flavor' is sufficient to effectively promote biocontrol in the world's farming systems.

Biological control through a 'diffusion of innovations' lens

From our global analysis, we realize that biological control innovations have diffused to varying extent within social systems, be it farming communities or individual growers, academia, or online societies. In terms of farmer adoption in North America, we can confidently say that we have fallen short in securing wide-ranging adoption of conservation biological control, as compared e.g., to pesticide seed coatings, prophylactic insecticide sprays or transgenics. As biological control practitioners, we are left to wonder why these scientifically-underbuilt, environmentally-friendly, cost-effective and largely harmless technologies are not more popular with farmers or consumers. To understand so, we will base ourselves upon Rogers' (1962) classic 'diffusion of innovations' theory and have a critical look at information diffusion processes and associated key attributes of biocontrol technologies. Rogers' (1962) diffusion of innovation paradigm largely saw extension as a mechanistic, linear knowledge-transfer process. In today's Information Era however, knowledge transfer is far from linear and has become pluralistic, with multi-actor, multi-level and multi-dimensional information streams (e.g., Schut et al. 2014; Servaes and Lie 2015). Though Rogers' (1962) conceptual framework has become somewhat obsolete, we still consider it a valuable starting point to identify certain attributes of biological control that impede its broader diffusion and uptake.

Rogers' (1962) conceptual framework is composed of five sequential stages, through which an individual passes when exposed to an innovation (Fig. 2). Within this framework, we identify certain elements that impede diffusion of biological control innovations, as

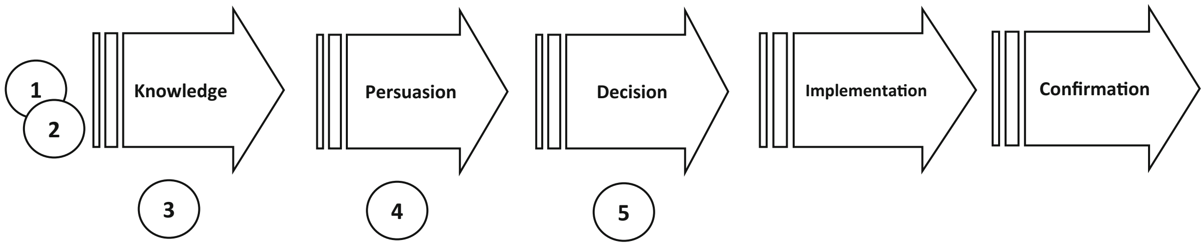

Fig. 2 Different stages within the 'innovation diffusion process', as adapted from Rogers (1962). Along this process, we list stages in which biological control innovations (e.g., concepts, technologies) tend to encounter difficulties or face critical shortcomings. Each of these components will be further elaborated in the text. Critical shortcomings: 1. Availability of sufficient knowledge on biological control innovations; 2. Needs and problems as perceived and prioritized by farmers; 3. Deficient knowledge base, and other key characteristics of the primary decision-making unit; 4. (Perceived) attributes of biological control innovations; 5. (Perceived) type of innovation-decision

ascribed to particular technology attributes, aspects of the decision-making unit (i.e., grower or general public), or components of the communication process. We organize these different constraints in four major categories: (a) prior conditions, (b) stakeholder characteristics, (c) perceived attributes of innovations, and (d) type of innovation-decision.

Prior conditions

Deficient knowledge on biological control innovations

Since the birth of the discipline in the early 1900s, substantial progress has been made in arthropod biological control research. With a steady output of nearly 1000 papers annually, researchers continue to generate critical ecological insights, pinpoint effective natural enemies, and devise valuable technologies. Nevertheless, there's an immense disparity in terms of amount of available knowledge and associated 'technology packages', not only between the three forms of biological control, but also between cropping systems, socio-economic contexts and geographies.

Augmentative biological control tops the ranks in terms of scientific knowledge, particularly in European greenhouse systems, where there's 'plenty of natural enemies' and substantial technological progress (van Lenteren 2012). Although classical biological control has secured numerous successes, the threat of invasive insects to the world's agriculture remains grossly under-estimated and ever-more relevant (Paini et al. 2016). Effective natural enemies have been identified for multiple invaders, but basic ecological research waits to be conducted for far more priority species. Lastly, scant scientific knowledge is available on conservation biological control, and solid empirical evidence has only recently been generated for certain habitat manipulation tactics (e.g., Gurr and You 2015).

A significant chasm exists in terms of biological control advances between temperate agro-ecosystems within developed nations, and (sub-)tropical systems. Among the >230 natural enemies that were commercially available in 2011, a meager 25, 23 or 26 could be purchased in a handful of countries within tropical Asia, Africa, or Latin America respectively (van Lenteren 2012). In farming systems across the tropics (except for rice), there's a virtual absence of sufficient and adequate information on pest ecology and associated opportunities to enhance or conserve natural enemies within agricultural fields (Sampaio et al. 2009). More so, for several major food staples and fruits in the developing-world tropics, virtually nothing is known about the identity of natural enemies, their field ecology or biocontrol potential (Wyckhuys et al. 2013). Also, 93% of the world's biological control research simply overlooks smallholder farming systems (Steward et al. 2014). In conclusion, though smallholders constitute the backbone of global food security (Tscharntke et al. 2012) and biological control might be tailor-made to their respective production contexts, we regularly have very little to offer them.

Divergent interests and priorities of farmers

Insect pests occasionally inflict substantial yield losses, but that is not always how farmers see it (e.g., Segura et al. 2004). Farmer perceptions, even more than economics, greatly influence on-farm pest management decision-making (Heong et al. 2002). Growers regularly prioritize soil fertility or water availability as factors that merit intervention, consider pest attack not to be economically significant, or see pests as an 'inherent part of nature'. When van Mele et al. (2009) interviewed African mango growers on insect natural enemies, farmers replied that not pests, but thieves, were an issue, and that weaver ants (*Oecophylla* spp.) effectively kept those thieves at bay. Making an effort to understand a farmer's priorities, even if those at first are only tangentially related to crop protection, is crucial to effectively promote biological control technologies.

Feeble agro-ecological knowledge base

Over the past 25 years, social scientists and entomologists alike have embarked upon initiatives to characterize farmers' agro-ecological knowledge (e.g., Roling and Jiggins 1998; Berkes et al. 2000). Co-author Jeffery W. Bentley, an experienced anthropologist, led one of the first endeavors to document farmers' understanding of biological control. "Nothing kills insects… except for insecticides" Honduran smallholders repeatedly told J.W. Bentley in the 1980s and 1990s. Obviously, some forms of biological control, e.g., parasitism by minute hymenopterans or the action of entomopathogens, are difficult to observe. But, rather surprisingly, farmers were also entirely unaware of insect predation by social wasps, conspicuous and active caterpillar-hunters that are omnipresent in local fields. Wasps (e.g., *Polybia* spp.; Hymenoptera: Vespidae) typically nest under the porch roof of rural homes, and fly back and forth, carrying a variety of insect prey items. Yet when J.W. Bentley asked farmers what wasps ate, smallholders would pause, as if they were thinking about something mildly interesting for the first time, and say "flowers, wasps must eat flowers." Though vespids do consume floral nectar, farmers were missing the point that predatory insects kill herbivorous pests. Over time, J.W. Bentley learned that Honduran farmers understood that *Solenopsis geminata* ants and spiders ate insects, but in general farmers thought that such predation was of little importance (Bentley and Rodríguez 2001).

Some of farmers' explanations of insect ecology were wide off the mark. When local 'campesinos' noticed that pests were increasing with the use of insecticides, they concluded that agro-chemical companies had put insects inside the pesticide bottles, instead of realizing that insecticides killed natural enemies (Shaxson and Bentley 1991). Honduran farmers who had received training on insect ecology did learn and remember some of the biocontrol concepts, but those were largely restricted to the action of large, conspicuous predators (Wyckhuys and O'Neil 2007a; Table 1). Scholars elsewhere in Mesoamerica also learned that local concepts of natural enemies were weak, at best. Most farmers in a Guatemalan study were completely unaware of natural enemies, even birds and other vertebrates (Morales and Perfecto 2000). Awareness of natural enemies was low in Chiapas, Mexico, even among farmers who had been trained to use bethylid parasitoids against the coffee berry borer (Segura et al. 2004). Asian studies equally documented low farmer knowledge of natural enemies, and Javanese farmers believed that predatory ladybugs were a pest (Winarto 2004). Farmers in the Philippines or Bangladesh thought that all insects were pests, and sprayed preventively (Palis 2006; Robinson et al. 2007).

Paradoxically, rural people can (and usually do) know a lot about insects, while paying scant attention to (minute) natural enemies. For example, a study in Nepal showed that Tharu-speaking villagers had 120 names for various small animals, particularly insects. Some misconceptions about natural enemies were astounding, e.g. that the praying mantis could pluck the eye from a person (Gurung 2003). Paul van Mele and colleagues studied folk knowledge of weaver ants *Oecophylla* spp. in Southeast Asia and in West Africa. They realized that farmers are largely unaware that ants kill insects, or believe that they only provide minor pest control services (van Mele et al. 2009). In Vietnam's Mekong Delta, a few growers did manipulate ants to control mango or citrus pests, especially those with a long tradition of tending orchard trees. This is one of the few documented cases where farmers do have a long-established tradition of applied biocontrol, which should be used as a strategic entry point to further explain the action of other (less conspicuous) natural enemies or frame biocontrol communication campaigns.

Table 1 Farmer understanding of the respective role of specific arthropod natural enemy groups, as contrasted between two different agro-production contexts and geographies

Natural enemy taxon	% correct answers		Knowledge difference between trained and un-trained communities
	Honduras maize ($n = 120$)	Vietnam cassava ($n = 83$)	
Dermaptera	23.3	–[a]	++ [b]
Hymenoptera			
Formicidae	24.1	–	+
Vespidae	15.8	–	++
Encyrtidae	0	15.9	++
Neuroptera			–
Lacewing adult	0	6.0	
Lacewing nymph	0	7.2	–
Araneae	7.5	–	–
Heteroptera	3.3	–	–
Coccinellidae	0.8	9.6	–
Diptera	0.8	–	–
Acari	0	15.4	–

Case study 1 covers traditional maize cropping systems in Honduras, where farmers since pre-Columbian times have managed an endemic, conspicuous lepidopteran pest (the fall armyworm, *Spodoptera frugiperda*) (Wyckhuys and O'Neil 2007a, b). Case study 2 covers cassava production in Vietnam, where local smallholders are facing attack by a recent invader, the cassava mealybug *Phenacoccus manihoti* (Uphadyay et al. unpublished). Farmers' agro-ecological knowledge was gauged through free-listing or photo-elicitation for either respective case study, and compared between communities with differing IPM training histories

[a] Not enumerated

[b] ++High, +Intermediate, – No notable effect

Easing the obstacles to farmer learning about natural enemies

Farmer knowledge of pests and natural enemies can be seen as a matrix that compares the "culturally important" with the "ease (or difficulty) of observation" (Bentley 1992). Cultural importance refers to items that matter to rural people themselves, not necessarily to biocontrol experts. Ease of observation is related to the size, color, habits and habitat of the organism that is being observed (or ignored). Smallholders are more likely to notice and know about large, bright, active, diurnal insects in field crops than about small, cryptic, nocturnal forest arthropods. This matrix yields us four types of local knowledge, each of which presents unique challenges and opportunities for sharing knowledge with smallholders about biological pest control.

Local knowledge is deep for topics that are culturally important and easy to observe

Many smallholders worldwide keep cats, not least because they kill rats and mice. The rodents are clearly a felt problem for people who store much of their food at home, and farmers easily notice their cats hauling off dead rats. Vertebrate pest control is a rich area for experts to learn from local people. Since farmers already know how to keep cats, biocontrol extension can simply reconfirm, validate or acknowledge this as exemplified in a recent training video on stored product pest management (Agro-Insight 2017).

Local knowledge is thin for things that are culturally unimportant, but easy to observe

Smallholders tend to ignore spiders, social wasps, predatory bugs or ants. These creatures are slightly more difficult to observe than house cats, but not much. Simple tools like insect zoos and agro-ecological drawings can capitalize on this area of local knowledge, though there are several limitations. For example, there is not always enough time to make multiple observations on certain organisms, or natural enemies such as robber flies and dragon flies are impractical to observe under those conditions (Luther et al. 2005).

Misperception arises for areas that are culturally important, but difficult to observe

Much of insect pest biology and ecology fits here. Smallholders are keenly aware of insect pests, yet cannot usually observe that there are male and female arthropods, which lay eggs or undergo metamorphosis. All of this can be taught, although it is more difficult to observe in the field than the actions of larger predators. People may reach the wrong conclusion if they spend energy thinking about difficult topics, but without the proper tools and concepts. For example, folks may decide that insects are spontaneously generated and never die. Once such kind of misperception is held in mind, it is difficult to dislodge. Extension must carefully acknowledge farmers' beliefs and explain the best that modern science has to offer, drawing upon logic and analogies (e.g. "insects mate, just like other animals") and using animations, diagrams, and photos.

There may be no local knowledge at all for the culturally unimportant and difficult to observe

The bulk of farmers across the globe are entirely unaware that entomopathogens, parasitoids, nematodes, or even sterile male flies even exist. It is tempting to conduct such research-and-development on those topics behind the backs of farmers. However, we are learning that, for example, the great success of introducing and liberating parasitoid wasps to control mealybugs in Africa and Asia is now being undone as farmers apply insecticides on cassava (Bentley 2014; Wyckhuys et al. unpublished). This means that researchers must either educate farmers about parasitism or find other technologies to replace their earlier victory.

From knowledge to persuasion

Stakeholder characteristics

Socio-economic characteristics

Fear of yield loss, pressure from agro-chemical companies, lack of understanding of key ecological concepts, and individual decision-making processes all play a prominent role, and each can steer farmers away from biological control or lock them into calendar spraying. In South African avocado crops, education, age and land-owner status all affect a farmer's decision to adopt biological control, with young farmers being more likely to use biological control (van Eeden and Korsten 2013). Also, older farmers are less inclined to employ habitat management tactics with long time-lags until payoff (Pannell et al. 2006). Household-level income is another determining factor. In certain contexts, raising incomes trigger pesticide use and the number of discarded pesticide containers in a field can easily be indicative of farmer wealth (e.g., Heong et al. 2002). Gender equally plays a prominent role in the adoption of biological control, but has somehow been overlooked. Men and women know vastly different things about farm insects, and women may be more inclined to embrace and promote safe, environmentally-sound practices such as biological control (Christie et al. 2015). However, while Vietnamese women assume a lead role in pest management decision-making, they possess little or no knowledge about biological control and steer their husband towards insecticide-based pest control (Uphadyay et al. unpublished).

Personality variables

Farmer innovators and 'early-adopters' tend to be venturesome, cosmopolitan individuals who actively seek new information (Rogers 1962). Other farmers are born experimenters and inventors, who tinker with new technologies and—when allowed access to underlying (ecological) concepts—can become generators of locally-relevant biocontrol technologies. This is exemplified by the case of un-educated Honduran smallholders devising artificial food-sprays after learning that ants control key pests (e.g., Wyckhuys and O'Neil 2007a). Irrespective of their creativity, a farmer's attitude to risk can fast become a key impediment to the adoption of biological control. In Bangladesh, where farmers expect to lose 58% of their rice yields if they do not use prophylactic insecticide sprays (Robinson et al. 2007), it will be key to either target less risk-averse farmers or to promote biological control practices that provide tangible (and visible) benefit.

Communication behavior

Some farmers are exceptionally proficient in seeking advice and look for information through a range of channels, such as radio, extension bulletins, or newspapers (e.g., Robinson et al. 2007; Wyckhuys and O'Neil 2007b). Pesticide salesmen or agricultural technicians are also regularly consulted, but do not necessarily guide a farmer towards biological control. Lastly, peer pressure is highly influential in determining an individual's pest management decisions (Heong et al. 2002). Some of the above pressures and farmer-to-farmer dynamics can be effectively wielded to drive dissemination of biological control practices, by creating conditions for social learning (e.g., Rebaudo and Dangles 2013).

Perceived attributes of innovations

Relative advantage

Biological control can provide vast economic benefits to individual growers or land-managers (e.g., Zeddies et al. 2001), but those regularly remain invisible to farmers. Farmers tend to have a difficult time assessing value and relative advantage of biological control, especially of preventive innovations (e.g., Goldberger and Lehrer 2016). Hence, any lingering technical uncertainty amongst researchers over the effectiveness of e.g., habitat manipulation tactics, could hamper further efforts for up-scaling and farm-level promotion (e.g., Cullen et al. 2008). Not only is science-based valuation of cost-benefit ratios essential, its unequivocal on-farm demonstration to growers is critical. In US cotton or urban landscapes, consumers and farmers regularly value and even express a willingness to pay for biological control, but this may be challenging to attain for other farming systems or contexts (Jetter and Paine 2004; Naranjo et al. 2015). For commercial biocontrol agents, relative cost clearly may hamper adoption (Harman et al. 2010), unless lucrative niche market opportunities exist or can be created for farm produce.

Compatibility

Particularly in field crops, biological control success is highly context-dependent and can be affected by field size, crop management or agro-landscape context (Schellhorn et al. 2015). While parasitoid mass releases may be profitable for large-scale sugarcane growers, the same technology may be un-economical for small-scale growers in diverse landscape mosaics. Also, it's a delicate balancing act to successfully use biological control in a crop that still requires insecticide sprays. Lastly, habitat manipulation tactics may fail to take root on 'manicured' farms where growers do not recognize positive attributes of weeds or exclusively value flowers for their esthetics.

Complexity

The classic 1996 study of William Settle and colleagues shed light upon the intricate trophic processes within rice agro-ecosystems, highlighting the role of organic matter and decomposers in sustaining predator communities. Transferring the full breadth of those concepts to local smallholders has proven exceptionally challenging, even when relying upon intensive, observation-based training courses (Waddington et al. 2014).

Trialability

Farmer's ability to engage in informal field trials and small-scale technology evaluation is a key determinant for biological control adoption (Cullen et al. 2008). Though some natural enemies are available in small (dose-sized) packages, their on-farm evaluation tends to be far more complex and requires focused observation, patience and the right attitude. This contrasts with insecticides, which are regularly sold in inexpensive, small sachets throughout the developing world, and are thus highly appreciated by farmers who run low on cash or are interested in trialing them on-farm.

Observability

Some ecological processes and trophic interactions are difficult to be observed with the naked eye, and most farmers do not fully appreciate the action of insect-killing fungi or entomopathogenic nematodes. In CABI's Global Plant Clinics or 'Going Public' extension programs, a magnifying glass or microscope is facilitated to growers to help them visualize and appreciate the role of certain beneficial organisms. The ability to see the unseen not only creates a sense of wonder for farmers, but can be a 'game-changer' in their inclination to adopt biological control.

Type of innovation-decision

Some biological control interventions depend upon farm-level intervention by individual growers, while others require concerted action or deliberate information-sharing by groups of farmers (Epanchin-Niell et al. 2010). Though this need for collective action is frequently identified as key obstacle to biological control adoption and diffusion in developing countries (Parsa et al. 2014), one needs to take into account that it is inherent to human nature to over-attribute one own's behavior to situational factors (Jones and Nisbett 1971). This so-called 'actor-observer bias' can best be exemplified and remediated through case studies and role-playing (e.g., Doohan et al. 2010). Also, authority can play a decisive role in propelling biological control technologies, as evident for state-supported initiatives in China, Cuba, Mexico, or in certain classical biological programs.

Success in promoting biological control

As immediate response to Asia-wide, insecticide-triggered outbreaks of the rice brown planthopper, the Food and Agriculture Organization (FAO) developed in the late 1980s the Farmer Field School (FFS) approach (e.g., van de Fliert et al. 1995; Matteson 2000). Piloted with rice growers in rural Indonesia, FFS create a space for farmer education, collective learning and hands-on participatory research on IPM and biological control. FFS course curricula readily incorporate observation-based learning about insect ecology and agro-ecosystem functioning. A typical crop-based FFS consists of groups of 15–25 growers that meet at frequent intervals throughout the growing season, observing pest and natural enemy dynamics within a given field and comparing conventional pest management practices with alternative strategies. A central component of FFS is the so-called Agro-Ecosystem Analysis (AESA), through which teams of farmers observe the crop, take note of the soil condition, water level, crop developmental stage, and the presence of pests, natural enemies, diseases or weeds. Each team summarizes its findings in drawings, which then become the topic of (often lively) group discussion. Special topics reinforce certain themes, and the establishment of 'insect zoos' are often built into the curriculum to strengthen farmers' understanding of biological control processes, such as predation by spiders or dragonfly larvae.

Under the participatory FFS learning model, biological control social learning is enhanced through a set of components. FFS make strategic use of hands-on experimentation, exchange and critical analysis to improve knowledge and decision-making skills. For biological control concepts, FFS promote 'learning by doing', by observing field-collected organisms in an insect zoo, studying life cycles, conceptualizing food webs, or observing effects of insecticides on natural enemies in small field plots. Through AESA, participants examine different interactions at the level of a food web or farming system, and jointly reach informed decisions for further crop or pest management. Oftentimes experimentation and observation-based learning is complicated, e.g., when assessing insect parasitism, or when farmers have previously been (over-)exposed to information on pesticide use. Understanding complex ecological processes requires time and, though farmers are members of FFS teams, the learning process regularly remains individual.

Since their inception in 1989, FFS have spread to over 90 countries, have found a place in numerous government-run programs, and have been embraced by grass-roots organizations, NGOs and private sector actors. FFS gradually matured and evolved into full-fledged Community IPM programs (e.g., Matteson 2000), or development of co-learning platforms such as local farmer research committees, i.e., CIALs for their Spanish acronym (Ashby et al. 2000). Over time, FFS came to cover a wide range of topics and diverse agro-ecosystems. By 2001, FFS trained >1 million Indonesian farmers on IPM and biological control, and 18–36,000 groups had been established worldwide. In recent years, FFS have been deployed for tomato leafminer (*Tuta absoluta*) management in North Africa, and are being considered to promote conservation biological control in Asia's rice-cropping systems (Westphal et al. 2015).

Although FFS have been applauded for their creative approach in transferring complex concepts and bringing about large-scale pesticide reduction, they also encounter certain weaknesses. Through their intensive, nearly personalized, training approach, FFS do entail relatively high costs and also face certain issues with scaling (Schut et al. 2014; Waddington et al. 2014). In several Asian countries, government support for FFS has waned over the past decade, leading to escalating use of low-cost, generic and banned pesticides and—once again—insecticide-induced pest problems (e.g., Thorburn 2013). As a long-delayed echo from the early 1990s, mounting concern is now being voiced that deficient attention to farmers' ecological knowledge and social science facets of biological control will only further accelerate pesticide over-use (Gould 1998; Chen et al. 2013). The rice brown planthopper—prime target of the acclaimed FFS—may very well become the pest around which the world's entomologists have to converge (Bottrell and Schoenly 2012), to either learn from the past or re-invent the wheel.

Future outlook

Knowledge co-creation in the digital age

Everett Rogers' theory lies behind us, and has been challenged on its linear and phased view on change, development and decision-making. Through the ontological perspective of today's actionable theory, farmers are seen as active constructers of knowledge and dynamically manage their own decision-making process. Also, knowledge-intensive innovations (e.g., biological control) flow through multiple directions and are affected by multi-level interactions between biophysical, social and institutional components (Schut et al. 2014). Current scaling approaches do not necessarily take into account these complex dynamics, and remain firmly constructed around Rogers' diffusion of innovations pillars (Wigboldus et al. 2016). In today's digital or new media age though, there is a growing opportunity to incorporate complex system dynamics, which address collective or connective action (e.g., Ostrom 2010; Milgroom et al. 2016).

The new participatory approach on sharing knowledge and active co-learning incorporates a view on learning strategies (Servaes and Lie 2014). For particular innovations and types of social actors, different learning processes can be considered, such as transformative learning, social learning, experiential learning, or reflexive learning. For technologies such as biological control, learning regularly occurs through knowledge co-creation in which farmers acquire, interpret and integrate information from a range of different sources, including first-hand experience, personal contacts and (digital) sources. New media and ICT tools can support such learning processes and accelerate knowledge co-creation, and give indigenous or folk knowledge an appropriate place within the entire knowledge system and decision-making process. By using information and communication technologies (ICTs), the dynamic, interactive and non-linear character of change can then also be further exploited (e.g., Servaes and Lie 2015). Technologies such as mobile phones, tablets or laptops can facilitate information sharing and the co-creation of knowledge. Although today's world is infused with new technologies and communication tools, biological control advocates have not fully exploited their potential in promoting their technologies and practices.

Film, mobile phones and tablet-based learning

Within this field of learning and knowledge co-creation, film has proved its useful applicability. Film is an older new medium that can still make a difference in knowledge co-creation (Lie and Mandler 2009). Video can assume a variety of roles and functions, and can be employed for awareness raising and advocacy, stakeholder engagement, capacity-building, or even simple reporting and data collection. Video can stimulate innovation, by delivering critical concepts and triggering farmers to experiment (Zossou et al. 2009). The power of using film lies in its appropriate character and its multi-modal form of communication, and can be effective, especially in illiterate and low-educated environments (e.g., Bentley et al. 2016). In the agricultural sector, the use of video for capacity-building has flourished over the past decade and video-sharing platforms such as Digital Green, Video Volunteers, and Access Agriculture are fast gaining popularity. Farmer-to-farmer video has been effectively used to transfer complex concepts such as parasitism and insect predation, as demonstrated in the multi-lingual video 'Managing mealybugs in casava' (accessible on Youtube) that was produced by AgroInsight for the International Center for Tropical Agriculture, CIAT. The video-sharing platform

Access Agriculture contains a large section on crop protection, e.g., where videos on biological control can be viewed or downloaded.

Over the past two decades, the use of mobile phones has grown exponentially. Phones enable rapid sharing of information, and create countless opportunities to stimulate positive change. Many studies have addressed the potential of mobile phones (e.g., Ramisch 2016; Asaka and Smucker 2016), but only few have explored their use for educational purposes and learning. The instructional strategies should determine the choice of the medium that will be used, but this is hardly the case in practice. Despite those limitations, cellphones are increasingly used to deliver customized, point-specific information to farmers, e.g., through voice-based information delivery, radio dial-up or SMS-based extension (e.g., Aker 2011). Phones can also be tactically used to gather feedback regarding new technologies, embark on citizen-science initiatives, or collect first-hand insights into grower interests, concerns and needs (e.g., Jarvis et al. 2015).

Lastly, tablet-based approaches can equally address specific learning strategies in the co-creation of agricultural knowledge. In rural areas that are less connected through 2G, 3G, 4G or wifi, tablets may even be preferred over mobile phones. Tablet-based learning strategies are being piloted in Sierra Leone through Digital Farmer Field Schools (DFFS). The DFFS approach uses a digital technology model, is built upon principles of responsible innovation (Stilgoe et al. 2013), and blended with some of the former FFS training principles, such as group learning (van de Fliert et al. 1995). Initial testing shows that the DFFS create new opportunities for knowledge creation and exchange, and is culturally and technologically appropriate (Witteveen et al. 2016).

Use of digital tools to enhance social learning on biological control

In the field of complex agricultural problems and extension, social learning is particularly appropriate and effective. Social learning in essence captures learning processes within a social context (Beers et al. 2016), and creates space for different world views, constructions of realities and perceptions of knowledge. Social learning is in fact collective action and reflection in which diversity is recognized and local knowledge, cultural importance, farmer-to-farmer interactions and FFS-type learning principles are essential (Keen et al. 2005). In this section, we describe two elements of social learning as directly related to the transfer of biological control concepts, tools or technologies: access to ICT-based learning and the use of visuals.

Access to ICT-based learning

Inclusive digital development addresses participation through the use of ICTs. One of the fundamental conditions for participation is access, which can cover the following: (1) motivational access (i.e., motivation to use digital technology), (2) material access (i.e., possession of computers and internet connections), (3) skill access (i.e., possession of digital skills) and (4) usage access (i.e., usage time) (van Deursen and van Dijk 2009). All forms of access need to be addressed to guarantee participation and to aim for inclusive digital development. In this regard, there is an important distinction to be made between access, interaction (socio-communicative relationships) and participation (co-deciding) (Carpentier 2011). Though access to ICT tools may be limited e.g., in smallholder communities in the developing-world tropics, strong interpersonal socio-communicative relationships may compensate for this and can further facilitate social learning of biological control.

The power of visuals

Although radio may be a powerful medium for agricultural extension (Rao 2015), it cannot communicate with visuals and is thus ineffective in addressing complex issues such as natural enemy biology or ecology facets. Novel ICTs, such as laptops, mobile phones or tablets, can effectively enable the use of visuals and incorporate animations, diagrams, maps, photos or film in processes of social learning. Over the past decade, the field of visual research has gradually gained popularity (e.g., Rose 2016) and can be employed to assess how visuals can effectively be used in the promotion of biological control. Another relevant field is visual literacy. Some older works addressed this field in relation to agricultural extension (e.g., Boeren and Epskamp 1992), but work is urgently needed to gauge farmers' interpretation of visuals and their contribution to biocontrol social learning.

Tablets or cellphones are just some of several ICTs that could convey complex concepts and trigger social learning processes about the use of biological control. Practical instructional videos, photo-films or animated cartoons can be developed e.g., on habitat manipulation, insect life cycles, food-sprays or the use of banker plants, and help guide farmer decision-making in myriad biophysical, socio-economic or socio-cultural contexts. However, before even embarking on the development of advanced ICT-based training materials for biological control, it will be essential to use insights into "farmers' knowledge, attitudes, and practices" as a starting point (Litsinger et al. 2009). Also, by systematically examining specific biological control technologies through a 'diffusion of innovation' lens, one can pinpoint critical constraints and limitations to their further promotion and upscaling. In conclusion, in the new media age, near-limitless possibilities are at our hands to transfer and validate technologies, alter public perceptions, and reach a 'tipping point' for biological control. Yet, in the end, it is up to us to move out of our comfort zone, embrace social science approaches as much as new technologies, and make them work to our benefit.

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