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Biological control and integrated pest management in organic and conventional systems

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ABSTRACT

More resilient and sustainable approaches are urgently needed to minimize crop yield losses resulting from pest activity and reduce impacts of pest management on human health and the environment. Increasing implementation of biological approaches, including biological control, biopesticides, biostimulants and pheromones is a mutual high priority for sustainable agriculture leaders and practitioners, including those working in organic agriculture and Integrated Pest Management (IPM). While market and regulatory forces, and pest resistance to conventional pesticides are contributing to growth in implementation of biological approaches, they remain a very small percentage of the overall global crop protection portfolio. Barriers to greater adoption include many of the same barriers to adopting IPM techniques or transitioning to organic. Improved awareness and understanding of the histories and benefits of organic and IPM, goals and priorities shared by organic and IPM proponents and practitioners, and opportunities for accelerating adoption of biological approaches have potential to improve our combined effectiveness in overcoming these barriers. Strategies to speed adoption include increased education and extension on proven, ready-to-use biological control options; full cost and benefit accounting for biologically-based alternatives to chemical controls; and public and private sector policies to encourage biological control and reduce reliance on chemical controls. Both the organic and IPM communities of practice stand to gain from collaboration on common interests and goals.

1. Introduction

World population continues to increase and needs to be fed by a global ecological system under stress. As a result, there is expanded interest in a productive and ecologically sound agriculture that grows healthy food while protecting environmental integrity for future generations. Not all technologies that increase productivity are free of negative impacts on long-term sustainability. For these reasons, there is a need to develop approaches that are stable, resilient and sustainable as well as productive.

Resistance to insecticides, herbicides, and other pesticides has led to increasing application rates, higher crop losses, and mounting costs to farmers on a pesticide treadmill (Pimentel, 2005; Oerke, 2006; Heap, 2014). Greater pesticide use is increasingly linked to elevated health risks for exposed populations of farmers, farmworkers, rural populations, and consumers (Bell et al., 2006; Colborn and Carroll, 2007; Calvert et al., 2008; Mills et al., 2009; Bergman et al., 2013; IARC, 2014; Mesnage et al., 2014; Myers et al., 2016; Kim et al., 2017). Pesticides have adverse impacts on soil health, water quality, and wildlife habitat (Gilliom et al., 2007; Wightwick et al., 2010; Pisa et al., 2014; Stone et al., 2014; Stehle and Schulz, 2015). Subsidies for specific commodity crops encourage monocultures and inefficient use of inputs for their production (Fausti, 2015). The non-market costs of these adverse impacts can only be estimated, but on a global scale they impose a significant burden (Muller et al., 2017).

Both Integrated Pest Management (IPM) and organic agriculture offer approaches that reduce reliance on pesticides. Biological control is an ecologically sound opportunity in both organic and conventional farming systems and is a key element of IPM, a decision-making process and suite of science-based tactics used in both systems.

The purpose of this paper is to increase awareness of the common ground between IPM, organic agriculture, and biological control, and to communicate mutual priorities and opportunities for collaboration among researchers, educators, consultants, and farmers working in organic systems and IPM.

Biological control is a form of "ecologically based pest management that uses one kind of organism (the 'natural enemies') to control another (the pest species)" (Hoddle and Van Driesche, 2009). Natural

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enemies include parasitoids, predators, entomopathogenic nematodes, pathogens, competing microorganisms with or hyperparasites of plant pathogens, herbivores feeding on weeds and weed seeds, competitors for resources and organisms producing toxins, termed antibiosis or allelopathy (Flint and Van den Bosch, 1981; Hoy, 1994; Flint, 2012; Heimpel and Mills, 2017). Biological control can be naturally occurring; foreign agents classically introduced and established; released native or foreign agents augmenting populations; or conserved or enhanced populations of native or foreign agents. Augmentative releases can be inoculative, building a population that is expected to act over generations, or inundative, where the organisms released are expected to generate immediate reductions.

More broadly, biological approaches also include pheromones used for monitoring pest populations and to disrupt mating, sterile insect releases, and biopesticides which are pesticide formulations made from living organisms or the products of living organisms. Some biopesticide definitions include genetically modified plants or organisms other than plants (US EPA, 2018). Additionally, biostimulants are biological products some of which can reduce the impact of pest activity as a consequence of a complex of constituents or indirect mode of action that improves plant tolerance to abiotic stresses, and not as a result of the sole presence of a known plant protective compound acting directly on pests (Yakhin et al., 2017).

Organic and IPM researchers, educators, and farmers have long been recognized as pioneers and early adopters of biological control (US Congress, Office of Technology Assessment, 1995). The world-wide organic market grew in sales from U.S.$40 billion in 2006 to U.S.$90 billion in 2016 (Willer and Yuseffi, 2007; Willer and Lernoud, 2018). The U.S. is the largest national market for organic food in the world, with a 48% share of the global market (Willer and Lernoud, 2018). Between 2006 and 2016, sales of certified organic product in the U.S. grew from under U.S.$15 billion to over U.S.$40 billion in 2016 (Greene, 2017). Increases in sales have greatly outstripped the growth of land in organic production in the U.S., which grew from 1.7 million to 2.0 million hectares between 2008 and 2016 in the U.S., compared with growth from 30.6 million to 57.8 million hectares world-wide (Willer and Yussefi, 2007; USDA/NASS, 2010, 2017; Willer and Lernoud, 2018). The growth of the organic market has led to the adoption of organic methods by more farmers on more land, although growth has been slowing in recent years. It is more difficult to estimate IPM adoption rates, given that there is no single, ongoing program or standardized approach, but rather periodic and often disparate assessments (Vandeman et al., 1994; Jasinski and Haley, 2014; USDA CEAP, 2017). Assessment tools have included surveys and sets of crop- and region-specific IPM Elements or Guidelines to assess the extent to which available specific IPM tactics have been adopted (Boutwell and Smith, 1981; Green and Petzoldt, 2009). A directory of crop- and region-specific IPM tactics lists and assessment tools is maintained by the U.S. Department of Agriculture (USDA) IPM Centers (2018).

2. Origins of organic agriculture

Organic agriculture developed as a response to the negative health and environmental impacts caused by modern chemical technology (Steiner, 1924; Balfour, 1943; Howard, 1947; Rodale, 1948). Efforts to legitimize and popularize organic techniques were met with contempt, hostility and derision from many in the agricultural establishment, particularly government agency officials, researchers at publicly funded universities, conventional farming organizations, and the manufacturers of agricultural chemicals. The organic movement in the United States grew in the 1960s and 1970s as public awareness of the adverse ecological effects of pesticides increased (Carson, 1962). Various states, led by Maine, Oregon, and California, passed laws that recognized organic production methods and protected organic food with truth-in-labeling laws. The USDA undertook its first serious, in-depth study of organic agriculture in 1980 (USDA Study Team on Organic Farming, 1980). The USDA's recognition of organic agriculture was short-lived, and it soon renewed efforts to stifle organic agriculture (Youngberg and DeMuth, 2013). Despite efforts to suppress organic farming, many of the techniques used by organic farmers received renewed attention as low-input, sustainable, and alternative agricultural practices (National Research Council, 1989).

After a period of relative stagnation during the early and mid-1980s, the market for organic food began to grow rapidly, again driven by awareness of the risks posed by exposure to pesticides (Sewell and Whyatt, 1989). Private standards were developed by various organic farming organizations and the International Federation of Organic Agriculture Movements, now known as IFOAM-Organics International (IFOAM, 2014). However, various organized interests around the world did not consider private standards to be sufficient to prevent fraud and protect consumers. In the U.S., consumer and environmental groups concerned about fraudulent claims relative to organic products formed a coalition with organic farming organizations and the natural foods industry to call for recognition of organic agriculture and federal regulation of claims. The result was the passage of the Organic Foods Production Act as a part of the 1990 Farm Bill [7 USC 6501 *et seq.*]. The USDA's Agricultural Marketing Service (AMS) established the National Organic Program (NOP) rule following a 12-year process (USDA/AMS/NOP, 2000, 2019). The European Union established its regulation for organic agriculture in 1991, which has had subsequent major revisions (EEC, 1991, 2007, 2008, 2018). Canada established an organic regime for certification and labeling in 2006 (CAN/CGSB, 2015, 2018a,b). Several other countries have established their own national standards, including Japan (JMAFF, 2000, 2017), Korea (KMAFRA, 2011, 2017) China (CNCA, 2011), and India (APEDA, 2001, 2014).

3. Origins of IPM

Tactics now associated with IPM and organic agriculture have been used for thousands of years, including some low-risk compounds from botanical and mineral sources, preserving and encouraging predators and parasites, resistant varieties and physical removal of unwanted plants. These types of tactics predominated prior to the rapid growth in production of synthetic pesticides from less than 22,680 kg in the U.S. in 1951, to 635 million kg by 1977 (Bottrell, 1979). Over 450 million kg of conventional pesticides, generally produced from synthetic ingredients, were used across all U.S. market sectors in 2012, with just over 400 million kg of that use in agriculture. All global pesticide use totaled an estimated 2.6 billion kg in 2012 (Atwood and Paisley-Jones, 2017).

The terms "Integrated Pest Management" and "IPM" first entered the lexicon in the early 1970s. IPM evolved from the concepts of *integrated control*, developed in the 1950s in response to pest populations resistant to pesticides and pest outbreaks resulting from pesticide impacts on beneficial insects (Stern et al., 1959), and *pest management*, where multiple tactics, including monitoring and action thresholds, are used to keep pest populations below damaging levels. IPM is focused on pests, but tactics include managing nutrients for optimal plant health and improving soil health. such as increasing diversity and abundance of beneficial organisms in the soil.

IPM approaches include those that prevent, avoid, monitor and/or suppress, 'PAMS', (Coble, 2003) all types of insect pests, plant diseases, weeds, nematodes, vertebrate pests of food and fiber crops, and for structural, landscape and public health pests in communities. Suppression includes cultural tactics such as cover crops or mulches, physical methods such as tillage, chemical pesticides and biological controls.

4. Synergies between organic and IPM

Many of the pioneers of IPM practices were organic farmers (National Research Council, 1989). At the same time, many farmers considered IPM to be an essential step of the transition from conventional to organic production. Most organic standards refer to biological and other non-chemical techniques as the primary means of crop protection.

The IFOAM standards state that "[o]rganic farming systems apply biological and cultural means to prevent unacceptable losses from pests, diseases and weeds" (IFOAM, 2014). Such systems rely on balanced crop nutrition, biologically active soils, locally adapted rotations, functional biodiversity, habitat management, beneficial organisms, and other practices as the primary means to protect crops. The standards require organic producers to rely first on biological, cultural, and mechanical means to manage pests, weeds, and diseases (IFOAM, 2014 §4.5.1). The standards specify variety selection, rotations, intercropping, companion planting, mechanical cultivation, protection of natural enemies of pests, habitat management, introduction of natural enemies such as predators and parasites, mowing, mulching, grazing, and mechanical controls as among the options required. Only if these practices are not sufficient, a limited number of specific substances can be used to manage pests, diseases and weeds (IFOAM, 2014 §4.5.2). The pesticides allowed are limited to those that do not pose a significant threat to human health or the environment, and meet the principle of care, otherwise known as the Precautionary Principle (IFOAM, 2014 Appendix 1).

The U.S. NOP rule requires biological, cultural, and mechanical management practices to prevent pests, weeds, and diseases (USDA/AMS/NOP, 2000, 2019 §206(a)). The augmentation or introduction of predators or parasites of pest species is explicitly recognized as an organic practice (USDA/AMS/NOP, 2000, 2019 §206(b)(1)), as is the development of habitat for natural enemies of pests (USDA/AMS/NOP, 2000, 2019 §), and non-synthetic controls, such as lures, traps, and repellents (USDA/AMS/NOP, 2000, 2019 §206(b)(3)). Pesticides are permitted only when biological, cultural, or mechanical methods are insufficient to prevent or control the target species, the specific substance is included in an organic system plan approved by the operations accredited certification agent, and the conditions for using the substance are met (USDA/AMS/NOP, 2000, 2019 §206(e)).

Similarly, the E.U. regulation calls for prevention of damage caused by pests, diseases and weeds to rely primarily on protection by natural enemies, crop rotations, cultivation techniques, choice of varieties and species, and thermal processes (EEC, 2007 Article 12 §1(g)). The Canadian Organic Standards state that "pest, disease and weed control practices shall focus on organic management practices that enhance crop health and reduce losses due to weeds, disease and pests (CGSB, 2015, 2018a §5.6.1). Acceptable management includes cultural practices, and physical and mechanical techniques. The Japanese standard states that "noxious animals and plants" be controlled by cultivation, physical, and biological methods, either alone or in combination (JMAFF, 2000, 2017). Thus, organic agriculture is required in most places to take a biointensive integrated approach to pest management.

Biopesticides and plant pesticides from genetically modified sources are excluded from by organic standards in the U.S., Canada and the E.U. (USDA/AMS/NOP, 2000, 2019 §105(e); EEC, 2007 Article 9; CGSB, 2015, 2018a §1.4a). In the U.S. and Canada, the entire formulation—not just the active ingredients—must comply with the standards. Non-active or "inert" ingredients used in pesticide formulations approved for organic production are required to be classified as minimum risk (USDA/AMS/NOP, 2000, 2019 §601(m); CGSB, 2015, 2018b).

In undertaking the transition from conventional to organic, many producers will use an integrated approach to reduce the amount of pesticides used (Hill et al., 1999). Getting off the pesticide treadmill, replacing one pesticide with another as a primary strategy for controlling pests and responding to pesticide-resistant pests, requires a systems-based approach that relies heavily on biological control (Lewis et al., 1997).

5. Differences between organic and IPM

Organic and IPM overlap, but the two are not congruent. Organic agriculture is a system of production that acknowledges the importance of biodiversity, soil biological activity, and biological cycles (Davies and Lennartsson, 2005). In the U.S. and in most of the world, "organic" is a legally protected word that has a set of standards based on practices that use biologically based approaches to fertility and pest management for crop production (USDA/NRCS, 2016). IPM has multiple definitions including "a decision-based process involving coordinated use of multiple tactics for optimizing the control of all classes of pests (insects, pathogens, weeds, vertebrates) in an ecologically and economically sound manner" (Prokopy and Kogan, 2009).

USDA NOP standards require the use of IPM techniques and specifically mandate the use of biologically based pest management [7 CFR 205.206(e)]. Many successful organic farmers practiced IPM and biological control before transitioning as well.

Most pesticides are prohibited by organic standards. In the U.S., non-synthetic active ingredients are allowed if they are not prohibited. The standards include a relatively short list of allowed synthetic pesticides that were found to meet low-risk criteria that consider effects on human health and the environment, and compatibility with sustainable agriculture [7 USC 6518(m)]. Genetic engineering is excluded from organic production, as are biopesticides and plant pesticides made or derived from genetically modified organisms [7 CFR 205.105(e)]. One criticism or concern is that excessive reliance on a few relatively ineffective pesticides limits options for pesticide rotation and tank-mixed pesticide combinations. Maintaining the efficacy of the few pesticides used in organic production requires reliance on non-chemical means as a first line of defense.

In contrast, there is not a codified national standard for IPM in any country. However, IPM is mandated by multiple international and national certification standards in food and fiber production, including standards established by the Forest Stewardship Council, Rainforest Alliance, Food Alliance and Protected Harvest, and multiple multi-national supply chain standards including the Sysco Sustainable Agriculture Initiative and the Potato Sustainability Initiative (Green, 2009). IPM is also seen as a useful approach for meeting pesticide risk reduction goals (European Parliament, 2009). Most, but not all of these standards prohibit specific pesticide uses that would otherwise be lawful.

6. Biological control in organic farming and food systems

Organic farmers are expected to take an ecological systems approach to protect crops (Altieri, 1983; Lampkin, 1990; IFOAM, 2005). A meta-analysis shows that organic farms tend to support greater biodiversity than non-organic farms (Bengtsson et al., 2005; Hole et al., 2005). Organic farmers rely less on pesticides, resulting in lower risks from pesticide contamination (Baker et al., 2002; Baranski et al., 2014; Benbrook and Baker, 2014). All pesticides used in organic production are also permitted for non-organic production. Because pesticides used in organic production are subject to additional scrutiny for their human health and environmental impacts, these pesticides, except for Spinosad, are exempt from a food tolerance for residues. Before being permitted for organic production, botanicals and synthetic pesticides are reviewed by the National Organic Standards Board for their impacts on human health and the environment. The botanical insecticide nicotine and the rodenticide strychnine were added to the National List of prohibited substances for their toxicity and potential hazards to non-target organisms (USDA/AMS/NOP, 2000, 2019). The insecticide rotenone, which has had registration for all food uses cancelled in the U.S., was proposed to be prohibited for organic production under the USDA's NOP (USDA/AMS/NOP, 2018).

Thus, it stands to reason that organic farmers would be more receptive to the adoption and use of innovative biological control techniques than non-organic farmers. In a survey of producers in the Western U.S., researchers reported that 83% of walnut producers in California and 91% of pear producers in the Pacific Northwest with at least some organic management of their land used biological control (Goldberger and Lehrer, 2016). These included conservation practices, such as reducing the use of pesticides that harm natural enemies and enhancing natural enemy habitat, as well as the augmentative release of commercially produced natural enemies. These were respectively compared with 53% and 75% adoption rates of biological control of non-organic producers of the same crops in the same region. Organic status was one of the most significant factors of biological control adoption in the study.

7. IPM and biological control in conventional and organic agriculture

Major historical biological control successes include introduction of the vedalia ladybird beetle (*Rodolia cardinalis* Mulsant) in 1888 to control cottony-cushion scale (*Icerya purchasi* Maskell) in California, eliminating the pest in two years, and introduction of *Chrysolina hyperici* (F.) and *Chrysolina quadrigemina* (Suffr.) in 1945–46, reducing populations of the invasive St. John's wort weed (*Hypericum perforatum* L.) which is toxic to livestock, to 1% of their original size within ten years (Flint and van den Bosch, 1981; DeBach and Rosen, 1991).

More recent historical survey and sales data are not specific to conventional agriculture but include applications in organic production which represented 1.2% of total global agricultural land in 2016 (Willer and Lernoud, 2018).

Pest management benefits from conservation biological control are not well documented but have been estimated at U.S.$4.5 billion annually in 2008 in the U.S. alone (reviewed in Begg et al., 2017). Examples include apple production in many regions around the world where pesticide applications for mites are rare due to pesticide product selection and timing that preserve key beneficials (Hoy, 2016).

In the first national survey of IPM adoption, Vandeman et al. (1994) reported IPM was used on 50% or more of U.S. cropland, defining IPM as monitoring pest populations and use of economic thresholds for insect pests, disease and/or weeds, or for corn, rotating corn with other crops. Adoption ranged from a high of 74% of corn, 72% for potato, 59% for soybean, 52% for all vegetables, to 50% of all fruit and nut production. The study reported conservation of beneficials on 38% of all land in vegetables and 22% of land in fall potatoes, and augmentation with beneficials on 3% of all vegetables. Pheromones were used to control insects on 7% of vegetable and 37% of all fruit and nut land.

From 2003 to 2006, the USDA conducted a series of region-specific surveys on IPM adoption using a standardized approach. Over a total of 18,188 sample points across twelve regions, beneficial organisms were released on less than one percent of cropland (USDA CEAP, 2017). Conservation biological control was not assessed. Biopesticide use was reported on 6.7% of cropland. Monitoring and thresholds were used on 26% of land in production and crop rotation was used to control pests on 63% of cropland. Crops were primarily field crops including corn, soybean, wheat and cotton, with hay, rice, potatoes and barley in some regions.

Sales data provide additional insights for biological products. For example, annual biopesticide sales have grown from U.S.$512 million, representing 2.4% of the crop protection market in 2009 (Marrone, 2009) to U.S.$3 billion annually and 5% of the market in 2017. Sales are expected to grow at 10–15% per year, with potential to equalize with the conventional market requiring another thirty years (Damalas and Koutroubas, 2018). Nearly 90% of the commercially available microbial biopesticides derive from *Bacillus thuringiensis,* a tremendous risk as resistance inevitably expands. van Lenteren et al. (2018) estimate augmentative biological control with invertebrate and microbial organisms is applied on more than 30 million hectares globally.

Pheromone product sales were approximately U.S.$500 million in 2016 (Dunham Trimmer, 2017). Macroorganism sales, primarily beneficial insects, mites, nematodes, were by far the smallest segment, primarily sold to greenhouse and other protected production, at less than U.S.$50 million in the U.S. Koppert, a global leader in macroorganism sales, generated an estimated U.S.$150 million annual revenues.

8. Motivations and obstacles for adoption of IPM and organic practices

The adverse impacts of pesticides and their increasing ineffectiveness are motivating farmers to look at alternative methods to protect their crops. A frequent first step will be the adoption of biological and cultural practices, reduction of pesticide applications, and the use of reduced risk pesticides, and finally a systemic approach based on ecological principles. Such an approach has been called ESR or "Efficiency-Substitution-Redesign" (Hill and MacRae, 1996). Policies to protect the environment and human health are expected to drive pesticide reduction, but experience shows that regulatory approaches do not always result in the adoption of robust agroecological practices by farmers (Lamine, 2011).

Organic and integrated methods exist in a global context, but choices of techniques are driven by local conditions. With globalization and climate change has come an accelerated introduction of exotic pests, often with an absence of viable natural enemies (Perrings et al., 2010; Stoett, 2010; Diez et al., 2012). Biological control continues to offer a resilient and dynamic solution to dealing with exotic introduced pests (de Lange and van Wilgen, 2010; Brodeur et al., 2018; van Lenteren et al. 2018) and it has been suggested that introduced biological control agents have the ability to acclimatize to local conditions to become more effective natural enemies (Heimpel and Mills, 2017). Organic farmers were also early and widespread adopters of techniques involving microbial pesticides, such as *Bacillus thuringiensis*, and the introduction of hyper-parasites. Another example of hyper-parasitic biological control is the introduction of a hypovirus to control chestnut blight in North America in the mid-1900s (Heimpel and Mills, 2017).

Integrated systems research with biological control has taken place on organic farming systems in Europe and the U.S. going back to the 1970s (National Research Council, 1989; Altieri and Nicholls, 2004; Wijnands, 2006). Organic and integrated systems are gaining attention and interest in the international research community (Wijnands et al., 2018). According to a national survey of U.S. farmers who identified as transitioning to organic, the adoption of organic practices is driven by personal and family values more than by marketplace incentives (Brown et al., 2017). Other factors named by most farmers were concerns about the environment, potential enhancement of farm sustainability, and concerns about human health. Accessing expanding markets and potential increase in profits were reported by most respondents, but market-based motives were lower than values-based ones.

On the other hand, technical barriers to adoption are obstacles. Weed management was identified as the number one obstacle to organic transition in a national survey of farmers (Brown et al., 2017). Organic agriculture faces a yield gap (de Ponti, Rijk and van Ittersum, 2012). This can be at least partially overcome by greater biodiversity (Ponisio et al., 2015). However, more research, innovation, and technology transfer are needed to further close the gap (Muller et al., 2017; Niggli et al., 2017).

Longstanding obstacles to IPM adoption in general are also barriers to biological control use, including direct costs outweighing direct benefits to users; poor recognition and accountability for indirect costs of tactics with greater risks to health and environment; lack of incentives to overcome high direct costs to users despite indirect benefits to the public; incomplete information; complexity; high cost of occasional control failures vs. the relative simplicity; lower direct costs and greater reliability of conventional pesticide options including genetically modified crops; advisor conflict of interest; and inadequate and declining investment in public sector research, especially for development of techniques that do not lead to a product that can be sold for a profit (Bottrell, 1979; Flint and Van den Bosch, 1981; Sorensen, 1993; Wolf, 1998; Sappington, 2014). Drivers of adoption of biological approaches include improved worker and consumer safety, market demand, additional modes of action and delayed resistance, and lower regulatory approval costs and shorter timelines in many countries. In many cases, the research agenda and adoption of integrated and organic techniques are driven by various stakeholders including, but not limited to, farmers seeking risk reduction from pesticide use (European Parliament, 2009; Lamichhane et al., 2018). The principles of sustainable pesticide use emerged from this context, including prevention and suppression; monitoring; decision-making; non-chemical methods; pesticide selection; reduced pesticide use; anti-resistance strategies; and evaluation (Barzman et al., 2015).

Specific barriers to success with biological controls include lack of natural enemies effective against many target pests; insufficient information available to farmers and other practitioners; complex application techniques; selection of an ineffective organism for the target; poor health or efficacy of biological controls due to inadequate or failed production, storage or shipping practices; faulty release timing or release mechanics; cost of commercial production and registration; poor fit with the predominant distribution channels for crop protection products; rapidly changing ecological conditions; interference by unfavorable weather, natural enemies of the biological control agent or pesticide use; and interference with non-target organisms (Marrone, 2009; Flint, 2012; Heimpel and Mills, 2017; Lamichhane et al., 2018; van Lenteren et al. 2018)

9. Ongoing organic-IPM forum

Researchers, producers, and agricultural professionals formed an Organic and IPM working group in 2013 to share ideas on how best to improve communication, understanding and outcomes among those working on organic systems and IPM in agriculture and food production (Baker et al., 2015).

The Working Group was formed following a roundtable convened in November 2012 by the USDA Northeastern IPM Center and Red Tomato, a Massachusetts-based food hub. The roundtable convened national leaders of organic and IPM communities to discuss overlapping challenges and identify opportunities for collaboration between the two groups. The working group provides an ongoing platform for continued exchange of ideas, research and innovative solutions to challenges facing both communities. The group consists of sixty individuals nationwide, representing land grant universities, extension, private consultants, non-profits, government agencies and practitioners. Group members meet regularly by conference call, web and in-person meetings, and have produced several publications.

The working group's white paper explores shared interests and tactics including IPM in both organic and conventional systems, as well as the opportunities for synergistic partnerships between individuals and organizations working in organic and IPM (Baker et al., 2015). These communities have not interacted or collaborated to the extent possible, and misperceptions and distrust of motives and methods have worked to the detriment of their shared research, education and policy priorities. The forum has been effective in improving mutual understanding and appreciation, and members have worked to educate others to dispel misinformation and communicate the benefits of collaboration through publications and presentations.

Research, development and outreach needs are increasing for organic and IPM as demand for production with lesser impacts increases, often resulting in competition between organic and IPM researchers for resources. There is a need for policy and market incentives to encourage adoption of bio-intensive and organic practices to combat subsidies for conventional agricultural practices. High farmer retirement rates necessitate capacity building for a new generation of researchers and extension professionals to continue development of pest management solutions, including weed, disease and insect pests.

A synergistic partnership is key to addressing these shared challenges, as the needs of organic and IPM communities are not always identical but are often complementary. The authors posit, "the collaboration between organic and IPM must become a public-private partnership recognizing the need and opportunity for policy and market forces to work together to address these challenges and achieve our goals". The white paper has been viewed more than 3000 times in 29 countries since its release.

Two years after the white paper's publication, the working group published a position paper entitled *A Call for a Truly Sustainable Agriculture* (Kirschenmann et al., 2018), detailing the group's updated perspective on the current and future state of agriculture. The authors suggest that truly sustainable agriculture systems are about our relationships with nature and with ourselves, calling for a movement from single tactic, therapeutic interventions to natural systems management. There is room for organic and IPM systems to learn from nature and incorporate principles into agricultural systems that work with nature instead of against it. Similarly, economic systems must evolve in tandem with agricultural practices to enable these "truly sustainable" practices to flourish. The working group has self-published this paper and members have distributed it to their networks, inviting feedback and additional discussion about the content.

The working group has several works in progress including a fact sheet about regenerative agriculture in conjunction with the USDA Regional IPM Centers to disseminate information to practitioners, researchers, extension agents, and other stakeholders to improve understanding and awareness of the term and organizations advancing the concept, and to encourage the adoption of regenerative practices.

In the process of preparing the White Paper, the Organic and IPM Working Group identified several topics that are of interest for further development. Foremost is a calculation of the benefits of organic and integrated production, which requires more in-depth analysis than the white paper or this article permits. Because of economic externalities, not all the benefits of biological control are reflected in the value of the crop. Producers who release mobile beneficial organisms such as insect predators and parasitoids benefit other producers when those organisms migrate to neighboring fields. The producer making the release is not rewarded by the neighbors in most cases and may even have their populations reduced by pesticide applications that drift onto their property. As a result, collective action is often needed to make biological or cultural practices effective on an ecosystem-wide basis (Baker, 1988). Chemical control also results in loss of biodiversity. Herbicide drift has adverse impacts on non-target plant and arthropod species (Egan et al., 2014). As a result, producers will under-invest in biological control and over-invest in chemical control.

If the full costs and benefits of biological, cultural, and chemical controls can be estimated, then mechanisms to compensate producers who adopt biological control and reduce reliance on pesticides can be proposed.

Some of the unresolved topics are relevant to the social sciences. Adoption of integrated and organic techniques are behavioral choices with cultural, economic, psychological, and social components. The differences between how conventional, IPM, and organic producers adopt biological control technologies deserves further exploration.

Even with price premiums for organic food, and organic crops commanding higher profits than non-organic crops, non-organic farmers are still reluctant to invest in the transition to organic. One factor is the barrier of the three-year transition following the adoption of organic practices. Many producers perceive that organic techniques have higher costs and risks, and during the transition period, most producers receive the going non-organic market price. The development of a 'transitional' label might help offset some of the cost. The extent to which IPM producers compete with organic producers, and to which an IPM label could be used by transitioning farmers has not received attention.

10. Research, education, regulator, management priorities

The authors propose the following priorities:

a. An updated assessment of barriers to adoption of biological control: Several surveys of barriers to biological control have been conducted (Sheppard et al., 2006; Marrone, 2009), however an updated assessment of these barriers should be performed to better inform education, extension, research and policy work.
b. Increased education and extension about proven, ready-to-use biological control options: Education and extension through universities is a valuable component to increasing the adoption of biological control and efforts such as the Midwest Institute for Biological Control, connect students with specialists from various regions to provide a broader perspective on biological control topics (Illinois Natural History Survey, n.d.). Biological control companies can also play a role in educating their consumers on efficacy and other benefits of biological control products, such as residue and resistance management and human and environmental safety (Marrone, 2009).
c. Full cost and benefit comparisons, including external costs and benefits, for biological vs. chemical controls: Cost-benefit comparisons involving the loss of populations or species, disruption of community and ecosystem features are challenging, given that these costs are not easily accounted for in dollars (Simberloff and Stiling, 1996) and the impacts of pesticides on human health and the environment are not considered in their price (van Lenteren et al., 2018). A full comparison of costs and benefits will be an important step to assess the impacts of biological control in comparison with conventional pesticides. Existing methodologies to estimate economic losses and costs of implementing biological controls in specific pest-crop scenarios can be applied to find the full or true cost of agricultural production systems (Cullen, 1984; Jetter et al., 1997; TEEB, 2010; UN FAO, 2012; Schader et al., 2014).
d. Public and private sector policies to encourage research, extension and adoption of biological control, and reduction of reliance on chemical control: Public policy reform can be a powerful way to improve confidence and support for biological control. The reform process should be publicly available and include representation from a range of stakeholders (Strong and Pemberton, 2000). van Lenteren et al. (2018) suggest fast-track, full-zone (vs. individual state or country), and permanent registration (vs. requiring periodic re-registration) will increase use of microbial biological control and reduce product costs; and argue that a "conscious agriculture" where all stakeholders in the production and consumption chain will increase use of biological control by affording greater weight to environmental and health concerns to balance profit maximization and externalization of costs which dominate decisions in conventional agriculture.
e. Increased and accelerated research and education on alternatives to pesticides with documented negative impacts on the health of humans, animals, insects and the environment: Research, especially with participatory methodologies, will continue to play an important role in the quest for reduced pesticide usage. Involving farmers in the research process can help ensure risks associated with alternatives to pesticides are considered in study design and implementation. The dissemination of research results should also be inclusive of farmers, advisors and other practitioners to ensure sufficient understanding and adoption by these parties (Calliera and L'Astorina, 2018; Lamichane et al., 2018).
f. Research, education and extension on interactions between and successful integration of biological controls and organic-approved pesticides, such as spinosad: Several studies explore the interactions of biological controls and organic-approved pesticides (Biondi et al., 2012), however additional research, education and extension should be conducted to ensure viable use of biological controls in systems using organic-approved pesticides.
g. Biological control in integrated weed management that reduces or eliminates reliance on herbicides: A global catalog of biological control agents and target weeds includes all deliberate releases made through 2012 (Schwarzländer et al., 2018). This resource can serve to inform additional research and education on effective biological control agents for use in integrated weed management.
h. Development of technology transfer models for biological control option, in conjunction with the development of working models for biological control successes: Various practices for exchanging biological control agents and information exist, including informal and formal networks and databases of biological control agent releases, and collaborative research projects with shared benefits for scientists and practitioners, however room for improvement exists (van Lenteren et al., 2018). Additional opportunities exist to apply specific models to understand and explain the effects of biological control (Barlow et al., 2005).
i. Biological controls that will reduce or eliminate the use of the following pesticides: glyphosate, sulfur, copper, antibiotics, e.g., streptomycin, terramycin, neonicotinoids that are highly toxic to bees, chlorpyrifos and other organophosphates.

Collaboration between organic and IPM communities can help advance biological control and address common priorities and goals. Organic and IPM both utilize a systems approach to crop protection, using inputs as a complementary, rather than primary, tactic for pest management. Without support for effective and economically viable alternatives to conventional pesticides and herbicides, the balance between this systems approach and input-based models will continue to challenge organic and IPM producers.

11. Conclusions

IPM and organic are compatible approaches to agricultural production that both rely upon biological control as one tool for producers to use. Both reduce pesticide use, risks and adverse impacts. Collaboration among those who work with the two sets of practices can make progress towards the adoption of solutions to production challenges that would include biological control.

The Organic and IPM working group's 2015 white paper (Baker et al., 2015) provides several recommendations that are applicable to the priorities identified above. These include:

a. Increased public and private support for long-term interdisciplinary research that are relevant to both organic and IPM systems;
b. Expansion of outreach and collaboration between IPM and organic proponents, with compensation to farmers who provide ecosystem services such as augmentative releases of natural enemies and provision of natural habitat for natural enemies;
c. Elimination of subsidies and supports that reward unsustainable practices that encourage inefficient applications of pesticides and other farm chemicals; and
d. Enhanced incentives to develop, formulate, market and sell more options for biological pest control that can be used by both organic and IPM producers.

Above all, producers and researchers need to overcome their historic reluctance to work together outside of their respective approaches. Whatever differences remain, all stand to benefit from working together for a sustainable and regenerative food system.

CRediT authorship contribution statement

Brian P. Baker: Conceptualization, Writing - original draft, Writing - review & editing, Project administration. **Thomas A. Green:** Conceptualization, Writing - original draft, Writing - review & editing, Project administration. **Ali J. Loker:** Writing - review & editing, Project administration.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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