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Review

Diamondback Moth, *Plutella xylostella* (L.) in Southern Africa: Research Trends, Challenges and Insights on Sustainable Management Options

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Academic Editor: Suren N. Kulshreshtha

Received: 5 November 2016; Accepted: 30 December 2016; Published: 3 February 2017

Abstract: The diamondback moth (DBM), *Plutella xylostella*, is a global economic pest of brassicas whose pest status has been exacerbated by climate change and variability. Southern African small-scale farmers are battling to cope with increasing pressure from the pest due to limited exposure to sustainable control options. The current paper critically analysed literature with a climate change and sustainability lens. The results show that research in Southern Africa (SA) remains largely constrained despite the region's long acquaintance with the insect pest. Dependency on broad-spectrum insecticides, the absence of insecticide resistance management strategies, climate change, little research attention, poor regional research collaboration and coordination, and lack of clear policy support frameworks, are the core limitations to effective DBM management. Advances in Integrated Pest Management (IPM) technologies and climate-smart agriculture (CSA) techniques for sustainable pest management have not benefitted small-scale horticultural farmers despite the farmers' high vulnerability to crop losses due to pest attack. IPM adoption was mainly limited by lack of locally-developed packages, lack of stakeholders' concept appreciation, limited alternatives to chemical control, knowledge paucity on biocontrol, climate mismatch between biocontrol agents' origin and release sites, and poor research expertise and funding. We discuss these challenges in light of climate change and variability impacts on small-scale farmers in SA and recommend climate-smart, holistic, and sustainable homegrown IPM options propelled through IPM-Farmer Field School approaches for widespread and sustainable adoption.

Keywords: small-scale farmers; pest management; brassicas; farmer-extension-researcher networking; insecticide misuse

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1. Introduction

Brassica vegetables, like cabbage (*Brassica oleracea* var. *capitata*) and cauliflower (*B. oleracea* var. *botrytis*), and open leaf kales, like rape (*Brassica napus*) and covo (*Brassica carinata*), are the popular staple relish and most widely grown leafy vegetables in the tropical and subtropical regions of Southern Africa (SA), cutting across a wide range of cultures and agro-ecologies [1–5]. These vegetables are grown throughout the year [6] and form the fastest growing agricultural subsector that contributes significantly to national and regional incomes [6,7]. With the persistent droughts, extreme temperatures, and flooding challenges faced in field crop production due to climate change [8,9], irrigable small vegetable plots remain comparatively reliable as an attractive source of food and income for rural households, who make up over 80% of the farming community in SA [6,10] and whose farming systems are more vulnerable to effects of climate change [9,11]. On the other hand, African urban areas face high food demand because of rapid rural to urban migration, which has grown from 53 million to 400 million between 1960 and 2010, with a potential to increase to 600 million by 2030 [11]. As a result, high unemployment and low per capita income in the highly populated urban areas have created an ever increasing demand for food [11]; hence the need for horticultural expansion in rural, urban, and peri-urban agriculture (UPA) to meet fresh vegetable food demand, supplement incomes, and meet nutritional needs [10–12].

Despite doubling as a household income generating enterprise, brassicas also serve as an important inexpensive source of vitamins and minerals [7,10]. Due to the simplicity with which they can be grown, numerous small-scale farmers make a living out of brassica production, relying on the proximal urban markets [10,12–14]. Similarly farmers distant from the city typically rely on alternative markets [14]. However South Africa still exports brassicas (especially cabbage) to some of its regional neighbours, including Zambia (0.2%), Mozambique (3.3%), Angola (3.4%), Namibia (5%), Swaziland (6.5%), Botswana (31.4%), and Lesotho (46.3%) [15], thus lending credence to the theory of high demand against a production deficit in the region. The global demand for organically produced vegetables [16] has also significantly opened new lucrative markets for these African economies with the potential to substantially increase their Gross Domestic Product (GDP) if the required quality standards are met. This, however, is challenged by the scourge of the diamondback moth (DBM), *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), a cosmopolitan insect pest of brassicas [17,18].

The DBM is the major, ubiquitous, and year-round insect pest hindering the economic production of brassica crops in SA [17–19]. Small-scale farmers are facing difficulty coping with DBM damage-induced losses and management challenges [3,19–24]. The economic importance of DBM is derived from its exceptional pest status that originates from its genetic diversity, high and year-round abundance, high reproductive potential, high genetic elasticity, cosmopolitan distribution, multivoltinity, and continuous suppression of the pest's natural enemies by synthetic pesticides [5,18,25] and possible survival failures by efficient natural enemies in the pest's new invasion areas [26]. Global losses of leafy vegetables attributed to damage and control costs of DBM alone were estimated to be around US$ 4–5 billion [27]. Partitioning crop losses in SA under small-scale farmer conditions has not been explored in detail. However, in Kenya, an estimated 31% loss has been reported [28]. If uncontrolled, losses of up to 100% are possible [5,29], as has been reported in Botswana ([30]; and from personal observation during fieldwork in 2014 and 2015. There is little knowledge on the actual loss data of brassicas due to DBM in SA countries. However, cases of abandoning brassicas and changing production timing (i.e., concentrating only on winter production) as a means of infestation avoidance have been widely recorded [5,23,25].

Temperature is a critical climatic factor, which influences insect biological activities such as survival, reproduction, growth, development, geographical distribution, and fitness [31–33]. An increase in temperature reduces the time taken to acquire the number of degree-days required to complete the *P. xylostella* life cycle, thus decreasing its generation time and increasing the number of generations per year [27,32–34]. An increase in average temperature with global change may imply reduced overwintering time or a total absence of diapause for some economic insects [32,33], with consequent implications on pest management and food security. In addition, global warming has the potential to impair the potential of *P. xylostella* biological control if an increase in temperature disrupts the life cycle synchronisation of the host and its parasitoids [34]. Recent modelling data has predicted a decrease in ecological niches for some insects with climate change [35], and, similarly, invertebrate biocontrol agents are not an exception. Previous work reported broad lethal temperature limits for adult DBMs [36–39]: the minimum body temperature that 0% of the moths could survive, known as lower lethal temperature (LLT_0), was −16.5 °C. The maximum body temperature that 0% of the moths could survive, known as upper lethal temperature (ULT_0), was 42.6 °C. The minimum body temperature for 25% moth survival (LLT_{25}) was −15.2 °C, while the maximum body temperature for 25% moth survival (ULT_{25}) was 41.8 °C [37,38]. However thermal tolerance for its major parasitoids has not been fully studied [34,36,38]. Unless the thermal tolerance of the major parasitoids matches that of the host DBM and evidence is presented that these traits may have coevolved, parasitoid efficacy in the face of climate change may be compromised [26]. Without coevolution of thermal tolerance, DBM challenge may likely intensify due to conducive climatic conditions [37–41] that may stimulate increased pest activity (feeding, breeding, and migration) [26,38]. Therefore, without efficient control mechanisms, the DBM problem could continue to increase despite the intensive pesticide use, which to-date may have been short-term, ineffective, unsustainable and expensive [18].

In this paper, we review the status of DBM management in the context of practice in SA. Specifically, we examine the past and current DBM pest status, management practices by farmers, DBM research, and development linkages among member countries (or the lack thereof) in SA with special reference to small-scale farmers who are the most affected. We also analyse the perspectives of researchers, farmers, and agricultural extension agents regarding DBM management and identify challenges and principal areas that require cooperation. We propose research on sustainable climate-smart agriculture and the selection of compatible integrated pest management (IPM) components that provide effective management of the DBM under small-scale farmers in SA, in the context of current and projected climate change scenarios.

2. Horticulture and DBM in Southern Africa

Due to socio-economic challenges and high unemployment rates in SA [11], horticulture is fast transforming into an intensive production and high-income-generating enterprise [39,40]. However, despite large expansion in land committed to horticulture in the region, returns per unit land area are still minimal [41], mainly due to pest related losses and, in some cases, high production costs. In addition, small-scale brassica farming systems are dominated by low scale cultivation of non-rotated monocrops with heavy dependence on family labour and locally available inputs [4,13]. Due to this perception, the management of the DBM (and other pests) is an in-built farming practice based on prophylactic pesticide use with the intention to 'eliminate' rather than to 'manage' the pest; and therefore economic threshold levels based on insect pest monitoring and scouting are not observed [5,13,40].

Consumer perception is another driver to intensive pesticide use. Urban consumers are biased to aesthetically damage-free vegetables and their demand for such produce cannot be ignored as a driver to intensive insecticide use by the farmers [14,42]. For small-scale farmers, the market is typified by vegetable vendors under make-shift stalls in urban and peri-urban roadsides. These vendors are an important market link between small-scale farmers and the urban market as they not only determine the market price for different levels of pest damage but are also directly linked to consumers [2]. This vendor market, just like urban supermarkets, has the capacity to influence price and quality; it triggers the excessive use of pesticides as farmers compete to produce and supply shiny, damage-free, 'quality' brassicas to satisfy the 'market standards'. Research in SA, however, has not contextualized these and other market forces in the light of acceptable damage levels on leafy vegetables, especially with reference to DBM attack. Reports indicate that market rejection and strong legislative frameworks influence the chemical application behaviour of farmers [43], forcing them to change chemical use patterns as fear of market loss supersede concern for public health [44].

DBM damage substantially hinders production and marketing of brassicas in SA [17,18,25]. Farmers' perceptions and practices on the management of this pest in the region are not yet fully understood [39]. Research to date has been survey-based [5,20,22,40] and generalised on both insect pests and diseases for all horticultural crops. This approach generalised and limited the information that could be generated regarding a specific pest. One of the main features of climate change, amongst others, is the rise in global mean temperatures and prolonged hot weather conditions [9]. In SA, temperature is projected to increase by 1–3 °C by 2050 [45–47] and its effects are likely to be more pronounced in the drier tropics than the humid subtropics [8,9]. In laboratory experiments, DBM showed activity over a broad temperature range, measured as LLTs and ULTs [36,38]. This may mean that, under the currently projected climate change in SA, DBM pest status is likely to increase, exacerbating already failing management practices [18,25,48]. Field population peaks, determined by both pheromone trap catches and crop infestation scouting, were observed in the warmer austral summer [19,22,49]. Regardless of the population source, high temperatures were shown to hasten development and thus shorten life cycles in *P. xylostella* [36,37]. However, temperature may differentially affect organisms, such that different insect pests (hosts) and their associated natural enemies may develop at different rates and thus affect host-prey/parasitoids synchronisation [26,33,50,51]. Extreme temperatures eliminate natural enemies that are susceptible to very high/low temperatures, whereas divergence from thermal preferences also disrupts the temporal and spatial synchronization of host/parasitoid phenologies, resulting in a high risk of challenging pest (host) outbreaks [34,35]. An increase in atmospheric carbon dioxide levels associated with global climate change may also reduce the efficacy of biological control agents against DBM by precluding or reducing the production of plants' secondary metabolites, which are necessary for the recruitment of natural enemies as part of the plants' natural defence mechanisms [52,53]. This and the misalignment of host-natural enemy life cycles may affect the natural enemy's efficacy and thus jeopardise the future of biological control programs [26]. There is a scarcity of published literature on climate-related coevolution of DBM and its natural enemies for optimising the efficacy of biological control. Nevertheless, some researchers have recommended that IPM programmes aimed at improving efficacy under global climate change should develop resilient agro-ecosystems, which incorporate populations' evolutionary potential and buffers against climate change effects [26,51,54].

3. Why is Southern Africa Hard Hit by the DBM Scourge?

3.1. Vulnerability to Effects of Climate Change

Sub-Saharan Africa will continue to be the area most hard-hit by climate change effects, due to increased mean temperature and increased rainfall variability [9]. With a record of 0.5 °C regional temperature increase, [9,35,45,46] predicts a projected increase in temperature of 3–4 °C by 2080, reduced rainfall, and increased degree days, aridity index, and evapotranspiration gradients. These factors will increase stress on already debilitating horticultural ecosystems, especially pest management, through changed pest dynamics, spatio-temporal distribution and increased pressure. Insecticide resistance associated with high temperatures has been recorded in different species [55], including variations in *P. xylostella* susceptibility to some organophosphates [55,56]. Therefore, under current climatic projections in SA [9,38,57], it is highly unlikely that DBM populations will decline due to the physiological stress associated with high or low temperature scenarios [36]. Sub-Saharan Africa's majority of rural small-scale farmers remains at the core of food production, but their production ecosystems are the most prone to climate change effects [9,45,57,58]. Using a prediction model [45], between 8% and 22% field crop losses have already been reported in sub Saharan Africa.

3.2. Farmers' Behaviour and Insecticide Use

Details and comprehensive data on farmers' behaviour relating to pesticide usage on DBM in SA are lacking [18]. However, survey baseline results show that between 75% and 100% of farmers in SA totally rely on chemical insecticides (Table 1). By global standards, these farmers use the greatest variety of chemicals, highest application rates, and the highest application frequency [5,43]. Frequency of application ranges from once every three weeks to three times a week [5,20,43,59].

At any given time, brassica farmers possess at least two to six different insecticides [42] and up to five different insecticides have been mixed in a single sprayer tank without technical recommendation or manufacturer instructions [60]. This might result in unknown phytotoxicity and unwanted (and seldom known) chemical reactions into compounds, which are possibly more hazardous and persistent in the environment [61]. Such hazardous compounds, even when geographically concentrated in pattern, could create significant exposure to the environment and the public through non-occupational exposure, where individuals not directly involved with chemical use get exposed to the chemical hazards through a contaminated environment [61,62]. Magauzi et al. [63] and Macharia et al. [28] detailed pesticide-related illnesses in Zimbabwe and Kenya respectively, and it has been reported that various symptoms related to pesticide poisoning have significantly increased as most small-scale farmers misuse chemicals and do not use personal protective equipment (PPE) [64]. Moreover farmers tend to ignore or take for granted certain levels of illnesses from synthetic chemicals, which they feel do not warrant medical attention, as an expected normal part of farmwork [60]. Consequently, there is scant information on the details of health effects and costs related to pesticide exposure, as most cases go unreported [28,60,61]. However, Magauzi et al. [63] reported high organophosphate levels in young horticultural farmworkers' blood and also recorded 24.1% abnormal cholinesterase activity in 50% of the sprayers (occupational exposure) and 49% of workers entering previously sprayed fields (non-occupational exposure) in Zimbabwe. Khoza et al. [64] reported similar results with both organophosphates and organochlorines and further reported chronic illnesses that were often misdiagnosed and mistreated in health centres; possibly due to rampant pesticide incorrect use [65]. Similar results were also recently reported in Kenya [28], as supported by reports of high proportion of small-scale horticulture farmers using insecticides in Africa (Table 1).

Table 1. Proportion of small-scale horticultural farmers using synthetic insecticides in Southern Africa and other parts of Africa.

Country	Farmers Using Pesticides (%)	Reference
	Southern Africa	
Mozambique	100	[5]
Botswana	98	[20]
Zimbabwe	No data	
Zambia	75	[40]
Malawi	75	[40]
	Other selected African countries	
Tanzania	98	[60]
Cameron	90	[66]
Ghana	85	[67]
Kenya	No data	

Occupational exposure is exacerbated by inefficient chemical use by small-scale farmers [42,43,60]. This ranges from using inappropriate chemicals, incorrect dosages, and wrong application timing and targeting, to non-calibrated or poorly maintained and defective (often leaky) application equipment [1,42,68]. Mvumi et al. [65] also reported the first three problems on synthetic grain protectants in Zimbabwe. Leakages were observed to lead to about 29 mL of dermal exposure per person per hour [60], depending on leakage rates, which might be currently higher due to cheap and faulty spraying equipment from non-reputable manufacturers flooding the market. Other forms of inefficient use resulting in exposure include the choice of extremely hazardous chemicals (Class 1a and 1b by WHO standards) [1,20,40,42,61], the use of banned chemicals [42,60,61], applying chemicals using twig/leaf bunches or home-made grass brushes/brooms, making homemade 'insecticide cocktails', and tongue-testing to assess concentrations [43]. Due to economic challenges, farmers sometimes often procure pesticides from unlicensed and unscrupulous dealers, thus increasing the risk of exposure and the chances of fraud and adulteration [60,65]. Reports from Zimbabwe indicate a failure to adhere to safety withdrawal periods, presumably due to market pressure; inefficient chemical use (only 35%–50% of sprayed chemical reach the target organism) [67,68]; application of the wrong pesticides (e.g., fungicides on insects); and abuse associated with the need to clear last seasons' expired pesticides [13,67]. This uncontrolled misuse and overuse of insecticide was reported to have significantly contributed to the increased resistance and suppression of potential biological control agents [17,18,25,30].

3.3. Lack of Insecticide Resistance Research

The DBM has shown resistance to 91 active ingredients of agricultural chemicals worldwide, including 12 strains of *Bacillus thuringiensis* (*Bt*), between 1953 and 2014 [48,69–71]. Compared to other parts of the world, DBM insecticide resistance in SA is relatively low (see Figure 1). Farmers tend to rely on their personal observation of insecticide efficacy failures to detect resistance. Following resistance 'detection', farmers usually continue using the same active ingredients at higher frequency, higher dosages, or in cocktails with other 'powerful' chemicals, which exacerbates the situation [5,42,43,60]. Despite the widespread use of hard chemicals to combat DBM in SA, we have not found any published comprehensive study on DBM resistance to commercially registered pesticides in this region (Figure 1). Management options and extension recommendations have been based on reports from the relatively advanced economies (China, Brazil, India, Australia, Nicaragua, Pakistan and USA) (Figure 1). However, resistance is highly geographical and highly correlated to insect strain as regards chemical exposure history, hence 'foreign' recommendations may not be directly applicable to the spatially heterogenous nature of the SA small-scale farming communities.

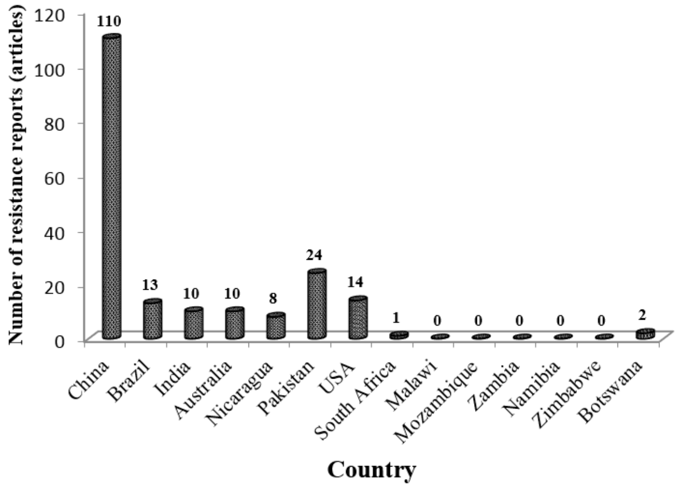

Figure 1. Selected country published reports on diamondback moth (DBM) insecticide resistance [48].

Consequently, farmers lack information on DBM resistance status in their respective localities to aid their pest control planning. This forces them to make their own, often ill-informed, decisions, mainly influenced by chemical manufacturers' advertisements, agro-dealers, and sometimes pesticide vendors ([40,43]; personal observation, 2014). Due to a lack of active pesticide control policies, farmers practice independent chemical choices and application (personal observation, 2014) without adequate consultation, resulting in 'dangerous' experimentations and haphazard chemical use with no regional or area-wide territorial regulations to aid Integrated Resistance Management [42,60]. In some cases, farmers smuggle 'effective' chemicals with noble modes of action from other countries into their home countries, where the chemicals have not yet been registered. Uncontrolled and inefficient use of these new pesticides results in early resistance development [54], which renders the modern pesticides ineffective by the time they are officially registered in the farmers' countries e.g., Hunter 500EC (Chlorfenapyr (pyrrole) 240 g/L) in Botswana (personal observation, 2014).

3.4. Low Research Attention

DBM research in SA is dominated by the public sector [2,24,25] where the agricultural ministries are custodians of agriculture and related work. In SA, countries with active DBM research are limited (see Figure 2). Conventionally research findings are delivered to the farmers through extension departments. This system is increasingly becoming inefficient due to declining public sector resources, the lack of farmer empowerment, and a lack of specialist staff in the sector [2,4]. The majority of SA research and development grants are funded externally [4,13], often coming with specific thematic areas that restrict researchers' flexibility. This may be a setback, as it limits scientists on tackling locally critical issues affecting small-scale farmers. This, coupled with low per capita funding and low capacity–building, exacerbated by 'brain-drain' to developed countries, limits research achievements [4,13]. Only a few SA countries can afford to keep specialist staff in the public sector, resulting in the disproportional distribution of research among SA member countries (Figure 2). South Africa and Kenya seem better off than the other countries, probably because of the presence of the Agricultural Research Council (ARC) and International Centre for Insect Physiology and Ecology (ICIPE), respectively, where DBM genetic, ecological, and IPM studies have mostly been conducted [23,28,71–76]. In South Africa, the ARC, in collaboration with industry and academic institutions, has conducted numerous studies on the DBM (Figure 3) on aspects including population dynamics, ecology, parasitism and predation, tritrophic interactions, and resistance breeding to *Bt* brassicas [21,71,72,76,77].

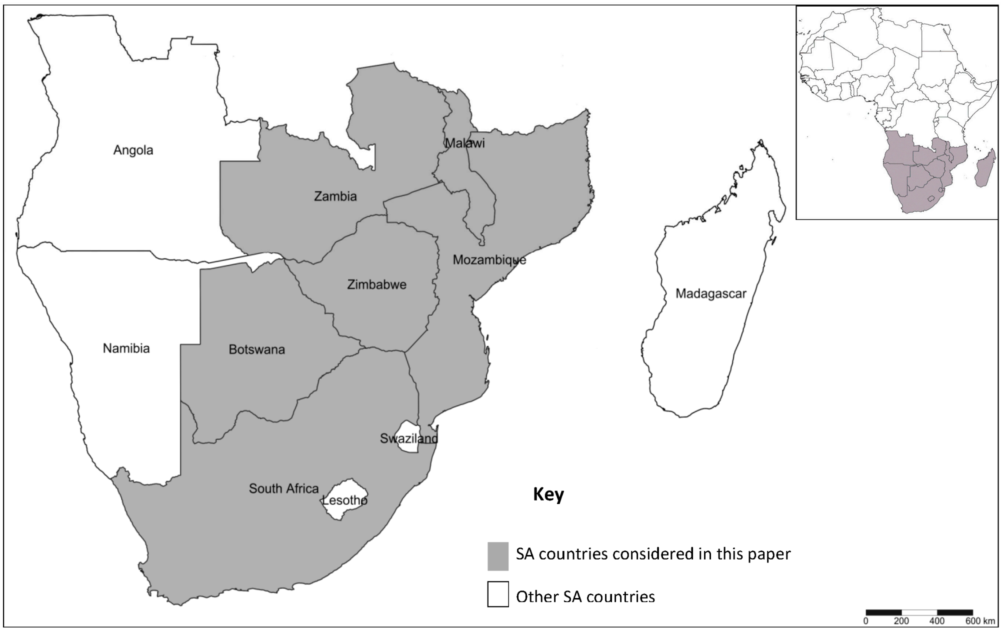

Figure 2. Countries in the Southern African region where DBM research has been conducted. This region appears in the high eco-climatic index of the world, where DBM persistence is year round and high [18]. * Namibia and Angola have very limited accessible research information on DBM, hence they were omitted from the map.

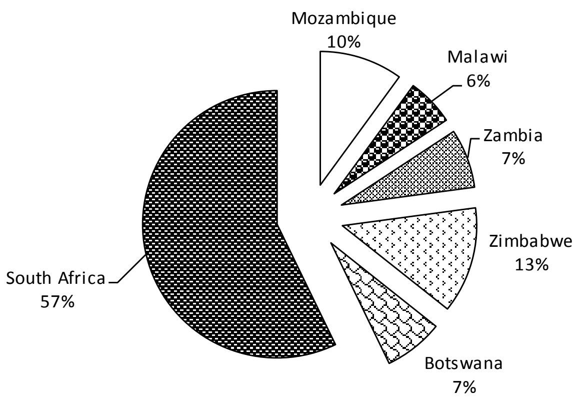

Figure 3. Proportion of publications on DBM in Southern African countries (1995–2015). (The data is based on physical counts of published papers and conference proceedings from respective countries).

In contrast, the other SA countries have limited research on DBM, with Zimbabwe being the only country contributing just over 10% of DBM research. Most of the DBM research is conducted by incapacitated horticultural research institutions that are often poorly funded [24]. The bulk of the research was survey-based, covering general farmer practices, identification, and spatio-temporal distribution of the DBM natural enemies (Figure 4). These surveys brought about vast knowledge on DBM predation and parasitism rates in the region [5,19,22,77]. Crop systems approached through intercropping with mustard, *Brassica juncea* (L) (Czern); onion, *Allium cepa* (L.); and/or garlic, *Allium sativum* (L.) (also making 22% (Figure 4)), have been over studied and duplicated in many SA counties, due to a lack of research coordination and information sharing [12,78,79].

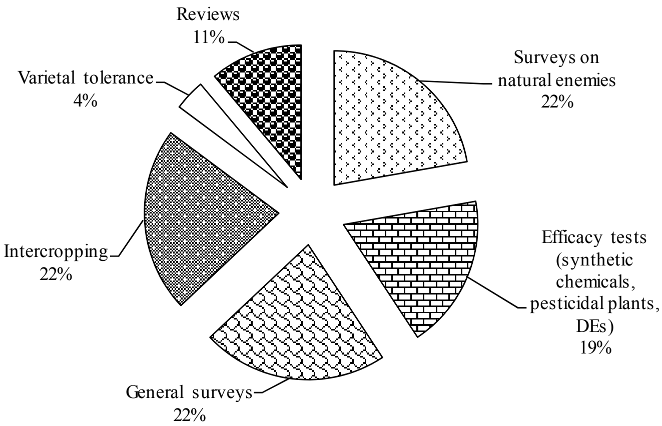

Figure 4. Proportion of published research articles on DBM in Southern Africa by theme (1995–2015). This is based on the physical checking of research themes for each of the publications in Figure 3).

Although SA has a long history of brassica production and an equally long acquaintance with DBM [25], research on its management seems to have started only about a decade ago with no data on the preceding years. Only recently, a synthetic pyrethroid (Cypermethrin), a *Bt* product (*B. thuringiensis* (*var. kurstaki*)), was tested for efficacy against DBM in Southern Africa, specifically Botswana [71,72]. Though this may be an important first step towards generating knowledge on DBM response to insecticides in the region, it needs to be expanded through testing area-specific populations for detailed territorial resistance profiling in all horticultural hotspots to aid planning on area-wide resistance management. Area-specific resistance assays may be critical in determining the susceptibility of DBM strains to current and future insecticides in different high production areas.

3.5. Lack of Regional Coordination in DBM Research

In 1984, the Southern African Development Community (SADC) (known as SADCC then) mooted and commissioned the Southern African Centre for Cooperation in Agricultural Research (SACCAR) for coordinated agricultural research in SA, which was partly funded by the Asian Vegetable Research and Development Centre (AVRDC) in the 1990s [80]. The AVRDC objectives in SACCAR were to coordinate vegetable research between and within SA member countries, develop novel vegetable postharvest preservation techniques, and, most importantly, develop an IPM program for the control of DBM in cruciferous vegetables for small-scale farmers [80]. Apart from coordinating regional research, SACCAR aimed to align agricultural research policies and priorities, identify constraints, promote cooperative research projects, strengthen national vegetable research centres, and encourage regional sharing and utilisation of scientific and technical information [80]. With headquarters in Botswana, SACCAR had sub-regional offices at reputable research institutions in Tanzania, Zimbabwe, Zambia, and Malawi in the early 1990s. However, as individual funding contributions from member states dwindled, independent donor organisations stepped in, diverting the organisation from its core mandates. To date, the organisation's activities are less visible on agriculture compared to the past, with high visibility on general economic constraints, labour-related issues, and the socio-economic welfares of selected member states. Thus, regional coordination and alignment of agricultural policies for concerted insect pest control efforts remain limited. However, there is hope in the recently formed Centre for Coordination of Agricultural Research and Development in Southern Africa (CCARDESA) (under SADC), which is targeting productivity and competitiveness of small-scale farmers across the region. The results of its activities are yet to be assessed.

The AVRDC, which is entirely committed to vegetable research, significantly sponsored regionally-coordinated research and capacitated national vegetable research centres in East Africa [2,4], but full expansion to SA was hampered by funding constrains [25,74]. Its major thrust was resistance breeding, farmer training, pest management, and general promotion of new technologies in SA that had proven successful in Asian nations [2,4]. To date, the results of its activities in the horticultural farming community in the region are certainly unclear, as is the case with SACCAR. The Asian Vegetable Network (AVNET), formed in 1989, successfully coordinated vegetable breeding and pest and disease control in Asia through the formation of strong dedicated sub-networks [81]. The advent of ICIPE in Kenya was an example of coordinated regional research in insect science, particularly in DBM crucifers [23]. Through this institution, Eastern Africa managed to conduct coordinated research aimed at DBM IPM [23,74,75]. ICIPE achieved DBM control in brassicas through the development and dissemination of biocontrol based IPM, using *Diadegma semiclausum* (Hellen) (Hymenoptera: Ichneumonidae) with complementary emphasis on a cropping systems approach [23]. Success was also achieved through a multidisciplinary approach, expert contributions, research funding, and supportive policies (national and regional) that enabled the granting of permissions to importations and releases of biocontrol agents [23]. Though this work did not effectively extend to SA, due to funding challenges (see discussion in [25]), the same model could be adopted in the DBM hard-hit SA region. Following the successful models of AVRDC and AVNET in Asia and ICIPE in East Africa, research networking may be a key mechanism for effective research aimed at achieving common goals for participating countries [23,81]. Southern Africa member states (Figure 2) can collaborate in the same manner for regionally consented efforts targeted at holistic DBM management. This networking is important to enable area-wide (regional) DBM management, as the pest's migration patterns and dispersal behaviour makes individual (farmer or country) methods ineffective [18,25]. A good example of this sub-regional collaboration is the recently-ended project aimed at combating the Asian fruit fly, *Bactrocera dorsalis* (Hendel), in Botswana, Namibia, Zambia, and Zimbabwe (BONAZAZI) under the technical assistance of FAO.

4. Possible Novel DBM Control Options

Climate-smart technologies aimed at maximizing production while promoting adaptation and mitigating the effects of changing environments are required [58]. IPM is a huge component of climate-smart agriculture, which, since the 1990s, has been generally agreed as the only sustainable and effective method of containing or managing economic pests, including the DBM [7,17,18,25,30,74]. Since synthetic chemicals offer short-time relief, several other management strategies have been investigated on a wide range of brassica agroecosystems, but IPM remains the most viable option [18,25,82]. IPM is that method of pest management that utilises all available and compatible techniques of pest management to reduce pest populations and maintain them below the crop economic injury levels [80,82]. The concept is aimed at eliminating the reliance on a single method of pest management in order to achieve better control and reduce or prevent development of pest resistance to a particular method [82]. This includes, but is not limited to, seasonal cropping (synchronised cropping calendar to minimize host plant availability), crop rotation, intercropping with non-host plants, enabling conducive environments for biological control agents, legislative plant host control (dead periods), the use of resistant varieties, and the judicious and minimal use (e.g., spot application) of environmentally benign insecticides (see [82]), which are applied only when absolutely necessary. In this system, insecticides from different chemical groups may also be rotated following legislation-enforced programs implemented and monitored by plant protection departments. Without legislative enforcement, synthetic insecticides continue to be used without due diligence despite widespread IPM awareness worldwide [43]. This is a practice that has caused deleterious consequences on DBM natural enemies including the reduction of their abundance and reduced efficacy in IPM systems [19,22,43,73].

Southern Africa is rich in natural enemies for DBM biological control [5,19,22,73]; therefore, the ecological consequence of widespread insecticide use, especially on these biological control agents, is a major concern [83,84]. Hence, a form of IPM aimed at reducing pesticide use and the promotion of selective soft insecticides (e.g., Pirimicarb, Pymetrozine and Spinosad (see Figure 5)) as its central tenets is the most crucial step in reducing the pesticide burden on the environment [84]. As explained earlier, biological control agents are currently dwindling due to intensive broad-spectrum chemical pesticide use and there is a danger that some of the natural enemy species may be completely lost unrecorded [83,84]. Therefore, unless the overreliance and unrestrained use of synthetic insecticides is significantly reduced, IPM and biological control measures in SA will continue to be hampered.

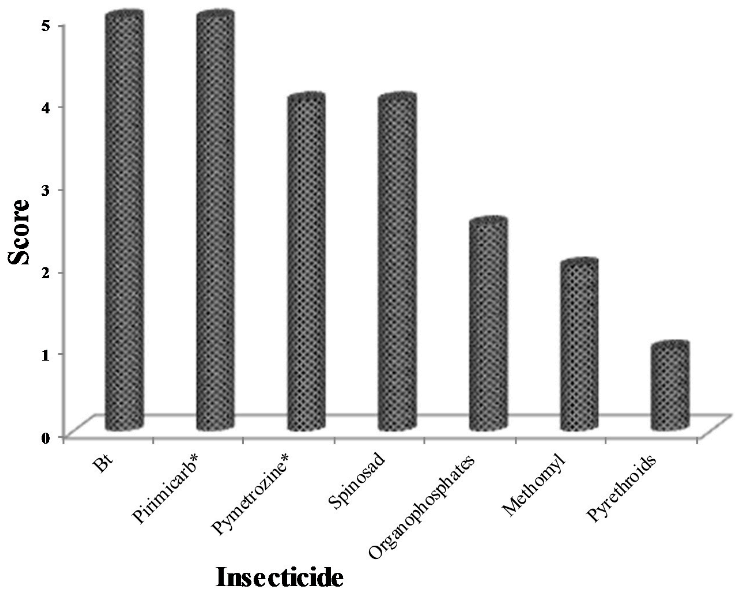

Figure 5. Common soft insecticides with high efficacy on the DBM and a low effect on its natural enemies (*Trichogramma* sp., *Cotesia* sp., spiders, lacewings and damsel bugs [84]). (Score: 5 = lowest effect on natural enemies, 1 = highest effect). *Insecticides not readily available on the market in Southern Africa (SA).

According to Walsh [84], *Bt*-based insecticides and Pirimicarb are the softest pesticides on DMB natural enemies, followed by Pymetrozine and Spinosad (Figure 5). Organophosphates, methomyl (a carbamate), and synthetic pyrethroids have high negative effects, particularly on *Trichograma* sp. and *Cotesia* sp., the most abundant and efficacious parasitoid species in SA [73,84,85]. Ironically survey results from SA, particularly Botswana [20], Zimbabwe [22], Malawi, Zambia [40], and Mozambique [5], show that synthetic pyrethroids, organophosphates, and carbamates are among the most commonly used insecticides in vegetable production. However, since genetically modified (*Bt*) brassicas were not accepted in SA due to social and environmental concerns [25], one of the sustainable management options is the rotation of *Bt*-based insecticides.

DBM is highly host-specific [86] (except in one observation of its survival on sugar-snap, *Pisum sativum* var. *macrocarpon* and snow peas, *P. sativum* var. *saccharatum* in Kenya [87]). Generally, moths do not oviposit on non-host plants; their host acceptance and oviposition is associated with a complicated integrated suite of chemical and physical cues [86]. Therefore, where soft insecticides are utilised, crop systems approached through the modification of agro-ecosystems and cropping practices can also be manipulated to confuse the adults' host finding techniques [88]. Research has shown partial DBM repellence success of cabbage intercrops with alliums through confusion in the chemical cues [12,78,79]. In such intercrops, natural enemies were shown to disperse and parasitise DBM at similar rates as in monocrops [88], evidence of compatibility between natural enemies and a cropping systems approach. There is potential in further improving this concept into a 'push-pull' cropping system technology by selecting appropriate repellent and attractant crops. Parasitoids are known to have originated from intricate mechanisms and are more efficient in heterogeneous than homogeneous landscapes. Push-pull intercropping that simultaneously improves habitat heterogeneity, conserves biodiversity by reducing hard chemical use, and improves refugia and nectar sources would improve parasitoid survival and efficiency [89]. This concept integrates climate-smart technologies as it utilizes ecosystem services for improved crop yields and quality.

Mass rearing and augmentative release of *Cotesia vestalis* (Haliday) (Hymenoptera: Braconidae) can be used to complement the conservation of existing faunal guilds [89] through the use of softer insecticides, as previously explained. Among the diverse range of DBM parasitoids, *C. vestalis* is the most widely distributed in SA [5,22,73,89], with the highest parasitism rates [5,21,22,73] and the only one tolerating the hot and arid tropical climates [5,17] typical of SA. The use of DBM entomopathogens naturally occurring in SA environments is also a novel possibility; for example, using *Metarhizium anisopliae* (Metchnikoff) [10] and a variety of other fungal microbes (as discussed in [25]).

5. Constraints to IPM Implementation and Adoption of Novel Sustainable Control Methods

5.1. Poor Understanding of the IPM Concept and Information Flow among DBM Management Actors

Currently, despite IPM being common, there is no evident decrease in pesticide usage even in areas where the concept is favourably viewed [83]. Farmers tend to adopt IPM based more on personal commitment level or influence by peers, rather than on recommendations from agricultural extension officers or researchers [52,82,83]. In Malaysia, [90] observed very little change in farming systems over a decade, particularly the use of synthetic insecticides despite widespread IPM campaigns. This can be attributed in part to lack of documented systematic IPM methodology or commercially prepared IPM packages with step-by-step instructions on how to use them [59,91]. Intensive research for a locally developed IPM system with simplified methodology, and inexpensive and accessible materials is therefore essential.

The major constraints to IPM adoption include a lack of awareness and knowledge [2,40], both of which are driven by the weak links and poor networking among the key players (Figure 6). Each player in the production and marketing chain has a crucial role to play; researchers develop the technology, extension officers transfer the technology to the end user (farmers), policy-makers create an enabling environment, and the agrochemical industry supplies the inputs (Figure 6). Vendors, supermarket chains, and horticultural export agents are key actors on the market and should be considered as part of the chain. Journalists, high profile multi-media agricultural reporters, and national broadcasters need to understand the principles of IPM for positive reporting to avoid misrepresentation of facts. The conceptual framework (Figure 6) shows that currently strong links (solid arrows) only exist between policy-makers and the agrochemical industry; researchers and funding agencies; and the agrochemical industry and media, all of which affect the farmers. Policy-makers have weak links with researchers, farmers, and the markets. The media also has weak links with researchers and extension agents, while having strong links with the agrochemical industry, explaining why horticultural programs on national broadcasters are currently dominated by product advertisements rather than IPM knowledge packages. It is therefore hypothesized that improving direct links between policy-makers and the markets, as well as the farmers, through pesticide residue limit assessment and enforcement, coupled with the development of knowledge packages that can also be passed through media and extension (Figure 6), would improve IPM adoption and reduce reliance on chemical pesticide usage.

This would also improve consumer and worker safety against pesticide exposure. Knowledge packages may include case studies of successful local IPM programmes in vernacular languages to enable farmers to appreciate and fully understand the techniques, the principles, and the benefits of the IPM technology.

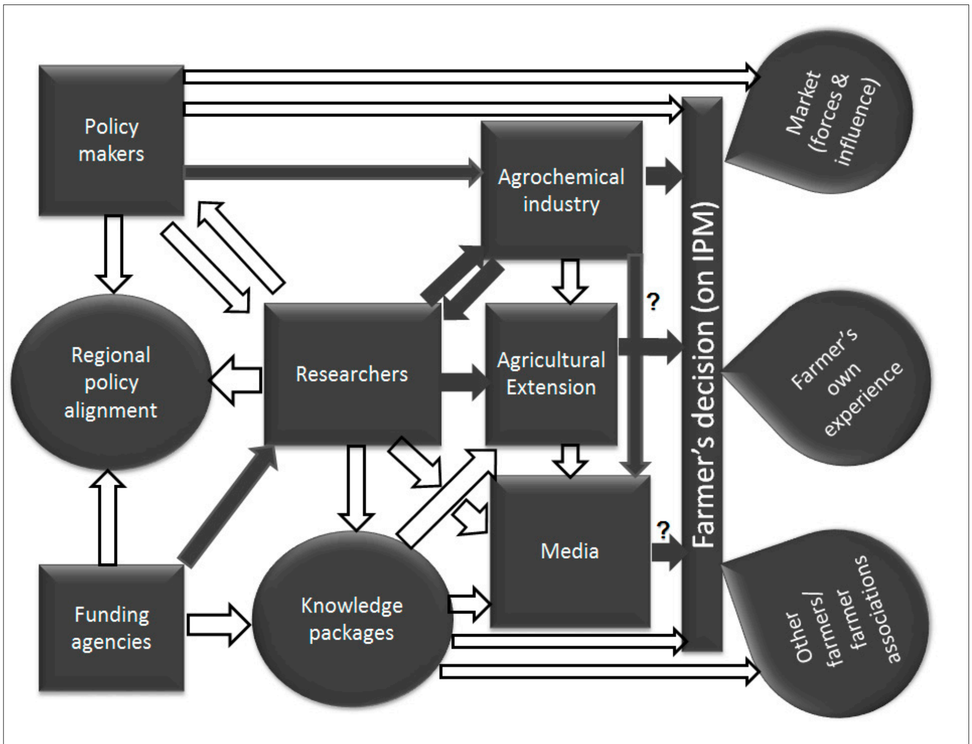

Figure 6. Perceived conceptual framework of links and information flow in DBM research in Southern Africa. The currently existing framework (solid arrows), the proposed framework (blank arrows), new suggested structures (circles), and links with both positive and negative influence on farmers' decision making (**?**) (Authors' own construction).

The introduction of IPM technology requires initial intensive training of the extension agents so that they cascade accurate and up-to-date information to farmers. IPM is complex process as it involves multiple components [82] and researchers often overestimate and equate their understanding of the concept with those of the extension agents, who also overestimate farmers' understanding [82]. In addition, donation of free agrochemicals by governments or donors and disproportional advertisements by the agrochemical industry, or a combination of such, does not only impede farmers' freedom of insect pest control options but also reduces their flexibility in decision-making [68,82]. Domination of synthetic pesticide research, manufacturing, and advertisements by the agrochemical industry, often in collaboration with academic researchers, coupled with lack of funding for research on non-chemical options, has further driven most agricultural extension agents and, subsequently, farmers to believe that the use of chemical pesticides is modern in agriculture [24,42,43,82]. This then overshadows the advances made in non-chemical pest control research, making farmers consider synthetic chemicals rather than non-chemical options as modern and first line of defence in DBM control [82].

Non-chemical control options, or a combination of such (in an IPM programme), are still largely considered as primitive due to a lack of understanding [40]. In most SA countries, extension work is dominated by the distribution of farming inputs (mainly fertilizers, seed, chemicals, etc.), with synthetic pesticides often being part of the package to the farmers [82]. This is also exacerbated by the farmers' high concern for access to inputs and the priority placed on these inputs [20] rather than the desire for knowledge or the use of non-chemical pest control methods [92]. This leaves little room for delivery of IPM knowledge packages through various training channels without input incentives. Requisite knowledge delivery to farmers is thus not valued as it should be, though it is key to understanding the concepts behind technologies enabling farmers to assess their risk and value for money invested, in order to make informed and independent adoption decisions [40,90,91]. Researchers and extension agents alike underestimate the amount of knowledge and information needed to convince small-scale farmers to adopt new technologies [91]. The latter's knowledge has not been able to keep pace with rapid agricultural technological changes, especially the dynamic DBM pest severity and management needs that continue to evolve in brassica production agro-ecosystems [42,91]. Increased knowledge has been proven to correlate with better pest management behaviour [43,75]. An understanding of the science behind building this knowledge in farmers is lacking among most extension agents in SA [86,91]. Knowledge is a dynamic system of cognition and is a sum of what has been learned, experienced, and perceived [91]. It involves observation, fact, and interpretative theory requiring intensive farmer participation [86,91,93]. As researchers and extension agents are more often providing information than knowledge, farmers' behaviour is unlikely to change under current scenarios [91,93]. Currently information is presented to farmers in a broad-spectrum format [91], but this has resulted in low uptake of technologies, as evidenced by low adoption. Information presented as such is often perceived by farmers as external rhetoric, associated with extension staff messages outside their farming systems [91,93]. This is so because most small-scale farmers in SA are risk-averse and unwilling to partake in voluntary schemes without immediate tangible incentives to which they are traditionally accustomed [82,91]. Until this mindset is changed through imparting knowledge and skills rather than information, for example through participatory IPM, the Farmer Field School (FFS) approach, or participatory action research/learning, co-learning and co-innovation approaches; adoption may remain a challenge.

There is a need to improve farmers' environmental knowledge base first, before the principles and practices of IPM can be emphasised [91,93]. For sustainability, the IPM packages need to be developed from local resources to avoid the constraints associated with external inputs and reduce strain on natural resources. For example, through development of participatory IPM in FFS, farmers may need to be trained in tritrophic interactions (plant-pest-natural enemy), pesticide toxicity, and its ecological consequences using farmer-tailored IPM curricula and approaches [90]. To foster positive attitudes towards IPM and improve its eventual implementation and adoption, there is need for awareness campaigns along the whole chain of stakeholders, alongside regular farmer trainings. As part of the reinforcement, it may also be beneficial if governments could feed eco-toxicological data into national pesticide registration policies to improve the adoption of IPM through the enforced use of softer and safer insecticides [43,62].

5.2. Weak Links between the Players in the Agroindustry

Parastatals, non-governmental organisations (NGOs), public national and international research institutions, independent researchers, private companies, and universities are not linked in a synergistic coordinated network, resulting in individual researchers and/or institutions independently presenting different technologies to farmers [2], sometimes with conflicting messages being conveyed. Sometimes host farmers may entertain a couple of researchers whose objectives are contradictory (personal observation, 2014), creating confusion and lack of trust among the farmers and extension agents alike [2]. The activities of the private sector, particularly the agrochemical industry, are scarce in literature. However, they are key to the procurement and distribution of chemicals and have a strong direct link with the farmers, which can be harnessed to propel other pest management options. Hence, there is need for collaboration of all stakeholders doing similar research and development work to fine-tune the broad-spectrum recommendations to specific relevant practices that enhance the fusion of the *emic* (inner perspective of the farmer) and the *etic* (outer perspective of the research/extension) [91,93]. Unfortunately, such platforms are rare.

5.3. Lack of Locally-Developed Well-Packaged IPM Practices and Procedures

The introduction of IPM should touch on various technical and social interventions [82]. The technical aspects mainly involve the techniques that farmers need to use to implement IPM in their brassica production systems. The development of step-by-step IPM methodology for cabbages in Asia through AVRDC and AVNET was key in the implementation and success of IPM in that region [82]. However, this has not been the case for SA. Direct adoption of Asian methodology may not necessarily apply in Africa due to different biophysical conditions, farmer practices, and socio-economic perceptions and circumstances [91]. Consequently, a SA IPM methodology tailored to specific local needs must be developed using participatory approaches to get farmers' buy-in. Furthermore, IPM monitoring tools to determine DBM economic threshold levels need to be scientifically investigated [29]. Local scientists and institutions have not developed IPM programs with regulatory and territorial chemical use boundaries for area-wide IRM, hence they still 'encourage' the use of any new chemicals [42,44]. These technical aspects also need to be locally refined and packaged within the small-scale farmer's contextual framework before a full IPM package can be presented and adapted for dissemination.

5.4. Lack of Policy Support

In Asia, the success of IPM programs was partly attributed to the crafting of enabling policies [80]. These included country agreements and harmonised policies to enable collaborative research, information-sharing, and the importation of natural enemies for key regional horticultural pests [79]. However, to the best of our knowledge, such enabling policies may still be lacking in SA. Global politics, as regards chemical use controls, is such that toxic pesticides are first banned in developed nations with effective regulatory and legislative policies. As regulations tighten in these countries, chemical manufacturing is reduced and the burden is passed on to developing countries by relocating factories and establishing subsidiaries in poor countries with governments that do not have effective regulatory controls [59,86,94]. In SA, this results in the uncontrolled use of extremely hazardous compounds, even years after they have been banned [5,20,61,94]. Some of the banned pesticides include DDT (only limited to mosquito control), Chlordane, Monochrotophos, Dieldrin, and Arsenic [94–96]. Therefore, this calls for strong technical and legislative capacitation of SA governments on issues of pesticide harmonized regulation and financial resources needed to develop and implement such legislations [42,81,82,94]. A classic example was Zimbabwe's successful development and implementation of a within-season pesticide rotational scheme and a closed season for the cotton bollworm *Helicoverpa armigera* (Hübner), achieved after a few years of strong legislative enforcement [24]. In SA, brassica farmers independently decide on the type of pesticide to buy, where to buy it, and when to apply it without any enforced regulation or legislation to consider. Though some general chemical regulatory frameworks may exist on paper, implementation is still a challenge in the region. Since brassicas are produced all-year-round, this promotes all-year-round unrestrained insecticide use on fresh vegetables that are supplied for public consumption, most of which are sometimes eaten raw. We therefore recommend a strong policy regulatory framework to control, minimize, and synchronize chemical use across all major horticultural production areas and markets. Mechanisms to implement and monitor the policy may also need to be clearly laid out right from the outset.

In some developing middle-income countries (e.g., Malaysia), threshold levels of pesticide residues permissible in crop products are well-laid out and monitored at different levels of the market value chain [88]. The lack of such policies in SA and the subsequent lack of regulatory frameworks account for the high pesticide residues in fresh products [2,42]. This is exacerbated by the cosmetic urban consumers' unconscious demand for damage-free brassicas [2,39,42]. The chronic nature of accumulated pesticide effect in humans makes the danger 'invisible' [63,64]. Though implementing residue-monitoring systems through the whole production and supply chain may prove logistically and financially infeasible for SA governments, the development of policy, legislation, and relevant monitoring tools may allow government officials to implement checkpoint systems across the vegetable production and supply chains.

Due to DBM notoriety and economic importance, we suggest that it may be necessary for SA governments to declare it a pest of regional economic importance, warranting policy recognition and consented governments' intervention, as is the case for tsetse flies, *Glossina morsitans* (Wiedemann); invasive fruit flies *B. dorsalis*; the larger grain borer, *Prostephanus truncatus* (Horn); migratory insect pests like the African armyworm, *Spodoptera exempta* (Walker); and African migratory locusts *Locusta migratoria migratorioides* (Fairmaire & Reiche). We recommend regional policy synchronisation, collaborative research, public awareness, farmer training, and IPM through Farmer Field School (IPM-FFS) initiatives in the management of *P. xylostella* synonymous with efforts applied to these other economic pests.

5.5. Taxonomic Confusion and Insufficient Adaptation of Biocontrol Agents to Release-Sites Climate and Bio-Ecological Conditions

The introduction of efficacious natural enemies has been marred by parasitoid taxonomic confusion and misidentification [18,97,98]. We have not found any reports of SA field-sourced parasitoid populations reared for mass release in DBM biological control programs in the region. *Diadegma semiclausum* and *C. vestalis* are currently the most common and efficacious DBM parasitoids in Africa [17,18,97,98]. *Diadegma semiclausum*, used for east African biocontrol programs, was once misidentified and exported as *D. mollipla* [99]. Due to misidentifications, release populations for the DBM control were imported from Taiwan, regardless of its local abundance in the horticultural hot-spots of Kenyan Eastern Highlands [74,98]. *Cotesia vestalis* is the most abundant and most efficient DBM parasitoid in SA [5,19,22,74,89], but some literature still refer to it as *Cotesia plutellae* (Kurdjumov) [18]. However, currently, *C. vestalis* populations from different climates are lumped together and considered as one species, despite observed biological differences [98]. Thus, molecular methods that can reliably separate biologically distinct but morphologically identical populations may be useful tools that can reliably confirm species' identity and hence improve the success of future biological control programmes [18,99].

Climate mismatching between parasitoid source areas and target release sites has led to the failure of most foreign reared but African released natural enemies [26,85]. This has now been exacerbated by unpredictably variable weather, increasing temperatures and fluctuating humidity caused by global climate change [9]. For DBM control, climate mismatching has previously been reported as a major setback for most biological control attempts [85]. Under the circumstances, climate matching between source area and target release site becomes an integral component of biological control programs based on parasitoid mass releases. This can only be achieved by a careful study of the thermal biology of the target parasitoid species. Mass introductions may then be targeted through acclimation, to suit areas of release [26,99,100]. Indeed, previous studies have recommended that thermal acclimation can significantly improve the fitness of laboratory reared insects upon introduction to wild conditions [100–103], and this approach has even been recommended for field releases using Sterile Insect Technique (SIT) [26]. It has been documented that biological control using predators and parasitoids should aim at developing resilient agro-ecosystems which maintain species' evolutionary potential to improve efficacy. This may be done through direct improvement in natural enemy genetic diversity and processes that encourage continuous in situ evolutionary adaptation [54].

5.6. Limited Alternative Control Options

In SA, the use of *Bt* transgenic brassicas have so far only been done in South Africa [96]. However, due to socio-political and controversial environment-related risks, it is yet to be commercialised in other SA countries [86]. Field and market observations from 2014 to 2016 showed that *Bt*-based insecticides are slowly filtering into the regional market. For example, pioneer *B. thuringiensis* (*var. kurstaki*) bioassays in Botswana showed 85.7%–94.6% reduction in DBM damage [71,72], but market availability still remains a challenge. However, this efficacy may also be short-lived, due to resistance development [69] as the insecticide is applied without a technical insecticide rotating scheme [68].

SIT has been successfully used for DBM management in Myanmmar [104], but its implementation in SA requires huge capital investment and substantial financial backup in addition to specialised human resources [105]. Furthermore, SIT is only effective in an area-wide approach, which may be challenging due to scattered distribution of small-scale subsistence farmers in SA.

Similarly, genetic engineering, through the release of insects carrying a male-selecting transgene, has equally managed to suppress DBM populations through the prevention of female progeny survival [106]. The same technique has been used successfully to control the fruit flies, *B. oleae* [107] and *Ceratitis capitata* (Wiedemann) [108], and the mosquito, *Aedes aegypti* (L.) [109]. However, this has not yet been considered in SA, probably due to the controversy surrounding genetically modified organisms. Nevertheless, it is an option worth considering in future DBM management programmes.

Strategies for developing varietal resistance in brassicas against DBM have not yet been fully exploited [82]. Modification of biochemical and morphological plant characteristics has also been unsuccessful [25,83]. Thus, despite its potential as an alternative non-chemical DBM control method, resistant variety development is still a huge challenge to biochemists and plant breeders [82] in SA. We have not found any research identifying chemical compounds or genes that are necessary to manipulate and cause brassicas to be completely non-preferred hosts for DBM [82].

6. Future Prospects and Research Needs

Future prospects in the sustainable management of DBM in SA lie in two principles, as outlined by [110].

(1) 'Do no harm'—the use of biologically- and environmentally-safe pest control methods with no or selective soft and safe insecticide use.
(2) 'Do good'—Improving farmer knowledge, consumer, agrochemical industry, and policy-maker awareness; policy reforms and regional policy harmonization; strengthening regulatory frameworks; and national and regional institutional capacitation.

Based on these principles, future research needs to identify and develop IPM-compatible components for the sustainable management of the DBM applicable to small-scale farmer circumstances in SA. Complementary to this, baseline information on the spatio-temporal population dynamics of DBM in relation to climatic parameters is needed. This may assist the area-specific determination of current population and pest management trends and how they correlate with environmental factors. This knowledge is important for the identification of gaps where development of new or improvement in existing IPM interventions is needed. Modelling the population and climate data will also assist in the development of predictive models that can be used in early warning systems to prepare farmers for possible outbreaks.

Farmer and extension staff capacity development can be achieved through participatory research using IPM in the FFS approach, on-farm farmer-managed, and researcher-managed trials. This will not only connect scientific findings with farmer's traditional knowledge and experience but will develop sustainable farmer-to-farmer knowledge-sharing platforms [58]. This also promotes co-learning, co-innovation and ownership of findings amongst all stakeholders which are essential ingredients for adoption. Success in technology adoption in various areas of agriculture was achieved in Asia through FFSs [44,91]. Farmer behavioural change may be possible through training, mass media awareness, legislative enforcement, and market condemnation of plant products exceeding set thresholds of pesticide residues [42,43,90]. Therefore, regular pesticide residue analysis may provide convincing evidence for governments to enforce regulations on chemical use on fresh vegetables. Where the regulations do not exist, they should be developed.

The future abundance and efficacy of *C. vestalis* under climate change remains uncertain. In addition, the synchrony and co-evolutionary adaptation between the host and the parasitoid also remains unpredictable [26]. Therefore, comparative abiotic stress tolerance studies of both the host and the parasitoid will provide insights into the needs for improvement of environmental fitness and efficiency of the potential parasitoids as an integral component of future IPM designs. Climate change was observed to impact insects negatively on the timing of life history traits, geographical shifts in species ranges, and the alteration of ecosystem interactions [55]. In addition, there are high-predicted rates of extinction in some species [111]. Therefore, comparative abiotic stress tolerance studies will not only enable the determination of whether it is the host or the parasitoid that is at high risk of extinction due to the impact of climate change, but will also be necessary to improve parasitoid field fitness for future release programs. Insect thermal biology and the ability to predict the impact of climate change on insect species are some of the most noble research findings of our time, yet adequate utilisation of this knowledge to improve pest management is still lacking, especially in Africa [35,55]. In the case of DBM, IPM systems need to have climate-resilient parasitoids capable of absorbing the 'shock' associated with the environmental changes due to global warming as a critical component of a broader climate-resilient IPM-FFS pest management systems approach [26,55].

Non-chemical control of *P. xylostella* may also be achieved through the manipulation of insect–host interactions. This may be achieved through brassica varietal resistance breeding and/or modification of the habitat by careful intercropping with attractant and repellent crops. As DBM larvae is generally monophagous, a varietal resistance option is promising if given full attention [6,82]. Research has also shown that *P. xylostella* moths do not oviposit on non-hosts. This means habitat management through agro-ecosystem manipulation may be an effective strategy to incorporate in IPM systems [81]. In light of the current knowledge, mere intercropping without careful selection of the repellent and attractant crops to enhance a 'push-pull' effect has not been very effective [12,78,79]. The 'push-pull' technology has been used for the successful management of cereal stem borers in eastern Africa [112,113]. This technology may be expanded, improved, and applied to economic pests such as the DBM in SA. For sustainability and cost-effectiveness, this technology may need to be geographically flexible in repellent crop selection to enable farmers to choose repellent crops naturally occurring and readily available in their localities. However, initial investment may be needed to conduct farmer participatory field research in the initial selection of potential candidate repellent and attractant crops.

7. Conclusions

SA is facing a serious DBM challenge and efforts towards its management are characterised by a variety of constraints. These vary from farmers' behaviour regarding insecticide choice and its use and/or misuse, a lack of health and environmental consciousness, a lack of locally-developed alternative control methods, a lack of regulatory enforcements, weak policy frameworks, and low research attention that is neither regionally-coordinated nor aligned for the achievement of common goals, all exacerbated by climate change and variability. The future of sustainable DBM control lies in IPM-FFS holistic approaches that include territorial IRM, cropping systems approaches (push-pull intercrops), soft and selective insecticides, area-wide pest management, biological control, the use of entomopathogens, and varietal resistance breeding developed in an IPM package. This should be supported by farmer and extension staff training as the founding principle of the approach to enhance in-depth knowledge and understanding of the IPM concepts, principles and procedures in a changing climate. There is also a need for exploring institutional or structural transformations to facilitate effective information flow and collaboration, sustainable uptake of IPM packages for improved crop protection systems, especially with respect to DBM and overall sustainable development.

Acknowledgments: The authors would like to acknowledge financial and technical support from Botswana International University of Science and Technology (BIUST) and technical support from the University of Zimbabwe (UZ). Many thanks to several anonymous referees, and the Eco-Physiological Entomology Research Team (BIUST) for the comments on an earlier version of the manuscript.

Author Contributions: All authors contributed equally to the manuscript. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sibanda, T.; Dobson, H.M.; Cooper, J.F.; Manyangarirwa, W.; Chiimba, W. Pest management challenges for small-holder vegetable farmers in Zimbabwe. *Crop Prot.* **2000**, *19*, 807–815. [CrossRef]
2. Saka, A.R.; Mtukuso, A.P.; Mbale, B.J.; Phiri, I.M.G. The role of research-extension-farmer linkages in vegetable production and development in Malawi. In *Vegetable Research and Development in Malawi. Review and Planning Workshop Proceedings, Lilongwe, Malawi, 23–24 September 2003*; Chadha, M.L., Oluoch, M.O., Saka, A.R., Mtukuso, A.P., Daudi, A., Eds.; World Vegetable Center (AVRDC): Shanhua, Taiwan, 2003.
3. Munthali, D.C. Evaluation of cabbage varieties to cabbage aphid. *Afr. Entomol.* **2009**, *17*, 1–7. [CrossRef]
4. Food and Agriculture Organization (FAO). *Evolving a Plant Breeding and Seed System in Sub-Saharan Africa in an Era of Donor Dependence*; FAO Plant Production and Protection Paper 210; FAO: Rome, Italy, 2011.
5. Canico, A.; Santos, L.; Massing, R. Development and adult longevity of diamondback moth and its parasitoids *Cotesia plutellae* and *Diadegma semiclausum* in uncontrolled conditions. *Afr. Crop Sci. Conf. Proc.* **2013**, *11*, 257–262.
6. Khonje, A.A. Research trends in horticultural crops in Malawi. *J. Crop Weed* **2013**, *9*, 13–25.
7. Ekesi, S.; Chabi-Olaye, A.; Subramanian, S.; Borgeimeister, C. Horticultural pest management and African Economy: Successes, Challenges and Opportunities in a changing global environment. *Acta Hortic.* **2009**, *911*, 165–183. [CrossRef]
8. Stathers, T.; Lamboll, R.; Mvumi, B.M. Postharvest agriculture in changing climate: Its importance to African smallholder farmers. *Food Secur.* **2013**, *5*, 361–392. [CrossRef]
9. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014: Synthesis Report*; Fifth Assessment Report (AR5); Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2014.
10. Maniania, N.K.; Takasu, K. Development of microbial control agents at the International Centre of Insect Physiology and Ecology. *Bull. Inst. Trop. Agric.* **2006**, *29*, 1–9.
11. Food and Agriculture Organization (FAO). *Growing Greener Cities in Africa*; First Status Report on Urban and Peri-Urban Horticulture in Africa; Food and Agriculture Organisation of the United Nations: Rome, Italy, 2009.
12. Katsaruware, R.D.; Dubiwa, M. Onion (*Allium cepa*) and garlic (*Allium sativum*) as pest control intercrops in cabbage based intercrop system in Zimbabwe. *J. Agric. Vet. Sci.* **2014**, *7*, 13–17.
13. Abate, T.; van Huis, A.; Ampofo, J.K.O. Pest Management Strategies in traditional agriculture: An African Perspective. *Ann. Rev. Entomol.* **2000**, *45*, 631–659. [CrossRef] [PubMed]
14. Momanyi, D.; Lagat, K.J.; Ayuya, O.I. Determinants of smallholder African indigenous leafy vegetables farmers' market participation behaviour in Nyamira County, Kenya. *J. Econ. Sustain.* **2015**, *16*, 212–217.
15. Department of Agriculture, Forestry and Fisheries. *A Profile of the South African Cabbage Market Value Chain*; Department of Agriculture, Forestry and Fisheries: Arcadia, South Africa, 2014.
16. Lubinga, M.; Ogundeji, A.; Jordaan, H. East African community trade potential and performance with European Union: A perspective of selected fruit and vegetable commodities. *ESJ* **2014**, *1*, 430–443.
17. Talekar, N.S.; Shelton, A.M. Biology, ecology and management of the diamondback moth. *Ann. Rev. Entomol.* **1993**, *38*, 275–301. [CrossRef]
18. Furlong, M.J.; Wright, D.J.; Dosdall, L.M. Diamondback moth ecology and management: Problems, progress and prospects. *Ann. Rev. Entomol.* **2013**, *58*, 517–554. [CrossRef] [PubMed]
19. Sithole, R. Life History Parameters of *Diadegma mollipla* (Holmgren), Competition with *Diadegma semiclausum* Hellen (Hymenoptera: Ichneumonidae) and Spatial and Temporal Distribution of the Host, *Plutella xylostella* (L.) and Its Indigenous Parasitoids in Zimbabwe. Ph.D. Thesis, University of Zimbabwe, Harare, Zimbabwe, 2005.
20. Obopile, M.; Munthali, D.C.; Matilo, B. Farmers' knowledge, perceptions and management of vegetable pests and diseases in Botswana. *Crop Prot.* **2008**, *27*, 1220–1224. [CrossRef]

21. Nofemela, R.; Kfir, R. The pest status of Diamondback moth (Lepidoptera: Plutellidae) in South Africa: The role of parasitoids in suppressing the pest populations. In Proceedings of the Fifth International Workshops on the Management of Diamondback Moth and other Crucifer Pests, Beijing, China, 21–24 October 2008.
22. Manyangarirwa, W.; Zehnder, G.W.; McCutcheon, G.S.; Smith, J.P.; Adler, P.H.; Mphuru, A.N. Parasitoids of the diamondback moth on brassicas in Zimbabwe. *Afr. Crop Sci. Conf. Proc.* **2009**, *9*, 565–570.
23. Nyambo, B.; Sevgan, S.; Chabi-Olaye, A.; Ekesi, S. Management of alien invasive insect pest species and diseases of fruits of vegetables: Experiences from East Africa. *Acta Hort.* **2009**, *911*. [CrossRef]
24. Tibugari, H.; Mandumbu, R.; Jowah, P.; Karavina, C. Farmer knowledge, attitude and practice on cotton (*Gossypium hirsutum* L.) pest resistance and management practices in Zimbabwe. *Arch. Phytopathol. Pflanzenschutz.* **2012**, *45*, 2395–2405. [CrossRef]
25. Gryzwacz, D.; Rosbach, A.; Rauf, A.; Russel, D.A.; Srivansan, R.; Shelton, A.M. Current control methods for diamondback moth and other brassica insect pests and the prospexcts for improved management with lepidopteran resistant *Bt* vegetable brassicas in Asia and Africa. *J. Crop Prot.* **2010**, *29*, 68–79. [CrossRef]
26. Chidawanyika, F.; Mudavanhu, P.; Nyamukondiwa, C. Biologically based methods for pest management under changing climates: Challenges and future directions. *Insects* **2012**, *3*, 1171–1189. [CrossRef] [PubMed]
27. Zalucki, M.P.; Shabbir, A.; Silva, R.; Adamson, D.; Shu-shen, L.; Furlong, M.J. Estimating the Economic Cost of One of the World's Major Insect Pests, *Plutella xylostella* (Lepidoptera: Plutellidae): Just How Long Is a Piece of String? *J. Econ. Entomol.* **2012**, *105*, 1115–1129. [CrossRef] [PubMed]
28. Macharia, I.; Mithofer, D.; Waibel, H. Health effects of pesticide use among vegetable farmers in Kenya. In Proceedings of the 4th International Conference of the African Association of Agricultural Economists, Hammamet, Tunisia, 22–25 September 2013.
29. Ayalew, G. Comparison of yield losses on cabbage from diamondback moth, *Plutella xylostella* L. (Lepidoptera: Plutellidae) using two insecticides. *Crop Prot.* **2006**, *25*, 915–919. [CrossRef]
30. Safraz, M.; Keddie, A.B.; Dosdall, L.M. Biological control of the diamondback moth, *Plutella xylostella*. A Review. *Biocontrol Sci. Technol.* **2005**, *15*, 763–789. [CrossRef]
31. Marchioro, C.A.; Foerster, L.A. Development and survival of diamondback moth, *Plutella xylostella* L. (Lepidoptera: Plutellidae) as a function of temperature: Effect on the number of generations in tropical and sub-tropical regions. *J. Neotrop. Entomol.* **2011**, *40*, 533–541.
32. Chown, S.L.; Nicolson, S. *Insect Physiological Ecology: Mechanisms and Patterns*; Oxford University Press: Oxford, UK, 2004.
33. Denlinger, D.L.; Lee, R.E., Jr. *Low Temperature Biology of Insects*; Cambridge University Press: Cambridge, UK, 2010.
34. Bahar, M.H.; Hegedus, D.; Soroka, J.; Coutu, C.; Bekkaoui, D. Survival and *Hsp70* gene expression in *Plutella xylostella* and its larval parasitoid *Diadegma insulare* varied between slowly ramping and abrupt extreme temperature regimes. *PLoS ONE* **2013**, *8*, e73901. [CrossRef] [PubMed]
35. Hill, M.P.; Bertelsmeier, C.; Clusella-Trullas, S.; Garnas, J.R.; Robertson, M.P.; Terblanche, J.S. Predicted decrease in global climate suitability masks regional complexity of invasive fruit fly species response to climate change. *Biol. Invasions* **2016**, *18*, 1105–1119. [CrossRef]
36. Andrew, N.R.; Hill, S.J.; Binns, M.; Bahar, M.H.; Ridley, E.V.; Jung, M.P.; Fyfe, C.; Yates, M.; Khusro, M. Assessing insect responses to climate change: What are we testing for? Where should we be heading? *Peer J.* **2013**, *1*, e11. [CrossRef] [PubMed]
37. Shirai, Y. Temperature tolerance of diamondback moth, *Plutella xylostella* (Lepidoptera: Yponomeutidae) in tropical and temperate regions of Asia. *Bull. Entomol. Res.* **2000**, *90*, 357–364. [CrossRef] [PubMed]
38. Nguyen, C.; Bahar, M.H.; Baker, G.; Andrew, N.R. Thermal tolerance limits of DBM in ramping and plunging assays. *PLoS ONE* **2014**, *9*, e87535. [CrossRef] [PubMed]
39. Kuntashula, E.; Silesh, G.; Mafongoya, P.L.; Bond, J. Farmer participatory evaluation of the potential for organic vegetable production in the wetlands of Zambia. *Outlook Agric.* **2006**, *35*, 299–305. [CrossRef]
40. Nyirenda, S.P.; Sileshi, G.W.; Belmain, S.R.; Kamanula, J.F.; Mvumi, B.M.; Sola, P.; Nyirenda, G.K.C.; Stevenson, P.C. Farmers' ethno-ecological knowledge of vegetable pests and pesticidal plant use in Northern Malawi and Eastern Zambia. *Afr. J. Agric. Res.* **2011**, *6*, 1525–1537.
41. Madisa, M.E.; Obopile, M.; Assefa, Y. Analysis of horticultural production trends in Botswana. *J. Plant Stud.* **2012**, *1*. [CrossRef]

42. Wandaat, E.Y.; Kugbe, J.X. Pesticide misuse in rural-urban agriculture: A case study of vegetable production in Tano South of Ghana. *AJAFS* **2015**, *3*, 343–360.
43. Williamson, S.; Ball, A.; Pretty, J. Trends in pesticide use and drivers for safer pest management in four African countries. *Crop Prot.* **2008**, *27*, 1327–1334. [CrossRef]
44. Timprasert, S.; Datta, A.; Ranamukhaarachchi, S.L. Factors determining adoption of integrated pest management by vegetable growers in Nakhon Ratchasima Province, Thailand. *Crop Prot.* **2014**, *62*, 32–39. [CrossRef]
45. Lobell, D.B.; Burke, M.B.; Tebaldi, C.; Mastrandrea, M.D.; Falcon, W.P.; Naylor, R.L. Prioritizing climate change adaptation needs for food security in 2030. *Science* **2008**, *319*, 607–610. [CrossRef] [PubMed]
46. Jack, C. *Climate projections for United Republic of Tanzania*; Climate Systems Analysis Group (CSAG)—University of Cape Town: Cape Town, South Africa, 2010.
47. Steynour, A.; Jack, C.; Taylor, A. *Information on Zimbabwe's Climate and How It Is Changing*; Climate Systems Analysis Group—University of Cape Town: Cape Town, South Africa, 2012.
48. Arthropod Pesticide Resistance Database (IRAC). Michigan State University. 2015. Available online: http://www.pesticideresistance.com/display.php?page=speciesarId=571 (accessed on 22 August 2015).
49. Mosiane, S.M.; Kfir, R.; Villet, M.H. Seasonal phenology of the diamondback moth, *Plutella xylostella* L. (Lepidoptera: Plutellidae) and its parasitoids on canola *Brassica napus* (L.) in Gauteng Province, South Africa. *Afr. Entomol.* **2010**, *11*, 277–285.
50. Dosdall, L.M.; Zalucki, M.P.; Tansey, J.A.; Furlong, M.J. Developmental responses of the diamondback moth parasitoid *Diadegma semiclausum* (Hellén) (Hymenoptera: Ichneumonidae) to temperature and host plant species. *Bull. Entomol. Res.* **2012**, *102*, 373–384. [CrossRef] [PubMed]
51. Sgrò, C.M.; Lowe, A.J.; Hoffmann, A.A. Building evolutionary resilience for conserving biodiversity under climate change. *Evol. Appl.* **2010**, *4*, 326–337. [CrossRef] [PubMed]
52. Kopper, B.J.; Lindroth, R. Effects of elevated carbon dioxide and ozone on the phytochemistry of aspen performance of an herbivore. *Oecologia* **2003**, *134*, 95–103. [CrossRef] [PubMed]
53. Sanders, N.T.; Belote, R.T.; Weltzin, K.F. Multitrophic effects of elevated carbon dioxide on understory plant and arthropod communities. *Environ. Entomol.* **2004**, *33*, 1609–1616. [CrossRef]
54. Gill, H.K.; Garg, H. Pesticide: Environmental impacts and management strategies. In *Pesticides—Toxic Effects*; Solenski, S., Larramenday, M.L., Eds.; Intech: Rijeka, Croatia, 2014; pp. 187–230.
55. Polson, K.A.; Brogdon, W.G.; Rawlins, S.C.; Chadee, D.D. Impact of environmental temperatures on resistance to organophosphate insecticides in Aedes aegypti from Trinidad. *Rev. Panam. Salud Publ.* **2012**, *32*, 1–8. [CrossRef]
56. Liu, F.; Miyata, T.; Wu, Z.J.; Li, C.W.; Wu, G.; Zhao, S.X.; Xie, L.H. Effects of temperature and fitness costs, insecticide susceptibility and heat shock protein in insecticide resistant and susceptible *Plutella xylostella*. *Pestic. Biochem. Physiol.* **2008**, *91*, 45–52. [CrossRef]
57. Metzger, M.J.; Bunce, R.G.H.; Trabucco, A.; Sayre, R.; Jangman, R.H.G.; Zomer, R.J. A high resolution bioclimate map for the world: A unifying framework for global biodiversity research and monitoring. *Glob. Ecol. Biogeogr.* **2013**, *22*, 630–638. [CrossRef]
58. Food and Agriculture Organization (FAO). *Identifying Opportunities for Climate-Smart Agriculture Investment in Africa*; Economics & Policy Innovations for Climate-Smart Agriculture, FAO: Rome, Italy, 2012.
59. Harvey, C.D. Integrated Pest Management in temperate horticulture: Seeing the wood for trees. *CAB Rev.* **2015**, *10*, 028. [CrossRef]
60. Ngowi, A.V.; Maeda, D.W.; Partanen, T.J. Knowledge, Attitudes and Practices (KAP) among agricultural extension workers concerning the reduction of the adverse impact in agricultural areas in Tanzania. *Crop Prot.* **2007**, *26*, 1617–1624. [CrossRef] [PubMed]
61. Baliga, S.S.; Repetto, R. *Pesticides and the Immune System: The Public Health Risks*; World Resources Institute: Washington, DC, USA, 1996.
62. Tsimbiri, P.F.; Moturi, W.N.; Sawe, J.; Henley, P.; Bend, J.R. Health impact of pesticides on residents and horticultural workers in the Lake Naivasha Region, Kenya. *Occup. Dis. Environ. Med.* **2015**, *3*, 24–34. [CrossRef]
63. Magauzi, R.; Mabaera, B.; Rusakaniko, S.; Chimusoro, A.; Ndlovu, N.; Tshimanga, M.; Shambira, G.; Chadambuka, A.; Gombe, N. Health effects of agrochemicals among farm workers in commercial farms of Kwekwe district, Zimbabwe. *Pan Afr. Med. J.* **2011**, *9*, 26. [CrossRef] [PubMed]

64. Khoza, S.; Nhachi, C.F.B.; Chikumo, O.; Murambiwa, W.; Ndudzo, A.; Bwakura, E.; Mhonda, M. Organophosphate and organochlorine poisoning in selected horticultural farms in Zimbabwe. *JASSA* **2003**, *9*, 7–15.
65. Mvumi, B.M.; Giga, D.P.; Chiuswa, D.V. The maize (*Zea mays* L.) post-production practices of smallholder farmers in Zimbabwe: Findings from surveys. *JASSA* **1995**, *1*, 115–130. [CrossRef]
66. Horna, D.; Falk-Zepeda, J.; Timpo, S.E. *Insecticide Use on Vegetables in Ghana. Would GM Seeds Benefit Farmers*; International Food Policy Research Institute (IFPRI), Environment and Production Technology Division: Accra, Ghana, 2008.
67. Abang, A.; Kouame, C.M.; Abang, M.M.; Hanna, R.; Kuate, A.F. Vegetable growers perception of pesticide use practices, cost and health effects in the tropical region of Cameroon. *Int. J. Agron. Plant Prod.* **2013**, *4*, 873–883.
68. Mudimu, G.D.; Waibel, H.; Fleischer, S. *Pesticide Policies in Zimbabwe: Status and Implications for Change*; Pesticide Policy Project; Special Issue Publication Series 1; Institute of Horticultural Economics: Hannover, Germany, 1999.
69. Tabashnik, B.E.; Malvar, T.; Liu, Y.B.; Finson, N.; Borthakur, D.; Shin, B.S.; Parck, S.H.; Masson, L.; Maard, R.A.; Bosch, D. Cross resistance of the diamondback moth indicates altered interactions with domain II of *Bacillus thuringiensis* Toxins. *J. Appl. Environ. Microbiol.* **1996**, *62*, 2839–2844.
70. Xia, Y.; Lu, Y.; Shen, J.; Gao, X.; Qiu, H.; Li, J. Resistance monitoring for eight insecticides in *Plutella xylostella* in central China. *Crop Prot.* **2014**, *63*, 131–137. [CrossRef]
71. Legwaila, M.M.; Munthali, D.C.; Kwerepe, B.C.; Obopile, M. Effectiveness of cypermethrin against diamondback moth (*Plutella xylostella* L.) eggs and larvae in cabbage under Botswana conditions. *Afr. J. Agric. Res.* **2014**, *9*, 3704–3710.
72. Legwaila, M.M.; Munthali, D.C.; Kwerepe, B.C.; Obopile, M. Efficacy of *Bacillus thuringiensis* (var. kurstaki) against diamondback moth *Plutella xylostella* (L.) Eggs and larvae on cabbage under semi controlled greenhouse conditions. *Int. J. Trop. Insect Sci.* **2015**, *7*, 39–45.
73. Kfir, R. Effect of parasitoid elimination on populations of diamondback moth in cabbage. In *The Management of Diamondback Moth and Other Crucifer Pests, Proceedings of the 4th International Workshop, Melbourne, Australia, 26–29 November 2001*; Endersby, N.M., Ridland, P.M., Eds.; The Regional Institute Ltd.: Gosford, Australia, 2004.
74. Löhr, B. Toward biocontrol based IPM for the diamondback moth in Eastern and Southern Africa. In *The Management of Diamondback Moth and Other Crucifer Pests, Proceedings of the 4th International Workshop. Melbourne, Australia, 26–29 November 2001*; Endersby, N.M., Ridland, P.M., Eds.; The Regional Institute Ltd.: Gosford, Australia, 2004; pp. 197–206.
75. Nyambo, B.; Löhr, B. The role and significance of farmer participation in biological control based IPM for brassica crops in East Africa. In Proceedings of the Second International Symposium on Biological Control of Arthropods, Davos, Switzerland, 12–16 September 2005.
76. Tonnang, N.E.Z.; Nodorezov, L.V.; Owino, O.; Ochanda, H.; Löhr, B. Evaluation of Discrete host-parasitoid models for diamondback moth and *Diadegma semiclausum* field time population densities. *Ecol. Model.* **2009**, *220*, 1735–1744. [CrossRef]
77. Bopape, M.J. The Management of Diamondback Moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), Population Density on Cabbage Using Chemical and Biological Control Methods. Master's Thesis, University of South Africa, Pretoria, South Africa, 2013.
78. Luchen, S.W.S. Effects of Intercropping Cabbage with Alliums and Tomato on the Incidences of Diamondback Moth *Plutella xylostella* (L.). Master's Thesis, University of Zambia, Lusaka, Zambia, 2001.
79. Karavina, C.; Mandumbu, R.; Zivenge, E.; Munetsi, T. Use of garlic Allium sativum as a repellent crop to control diamondback moth (*Plutella xylostella*) in cabbage (*Brassica oleracia* var. *capitata*). *J. Agric. Res.* **2014**, *52*, 615–622.
80. Opena, R.T.; Kyomo, M.L. Vegetable Research and Development in SADCC Countries. Available online: http://trove.nla.gov.au/work/7530097?selectedversion=NBD7890552 (accessed on 5 January 2017).
81. Green, S.K.; Shanmugasundaram, S. *AVRDC's International Networks to Deal with the Tomato Leaf Curl Disease: The Needs for Developing Countries*; Springer: Dordrecht, The Netherlands, 2007; pp. 417–439.
82. Maredia, M.K.; Dakomo, D.; Mota-Sanchez, D. *Integrated Pest Management in the Global Arena*; Commonwealth Agricultural Bureau International (CABI): Wallingford, UK, 2003.

83. Devine, G.J.; Furlong, M.J. Insecticide use: Contexts and Ecological Consequences. *Agric. Hum. Values* **2007**, *24*, 281–306. [CrossRef]
84. Walsh, B. *Impact of Insecticides on Natural Enemies in Brassica Vegetables*; Horticulture Australia Ltd.: Sydney, Australia, 2005.
85. Kfir, R. Biological control of the diamondback moth *Plutella xylostella* in Africa. In *Biological Control in IPM Systems in Africa*; Neuenschwander, P., Borgemeister, J., Langewald, J., Eds.; CABI Publishing: Wallingford, UK; Cambridge, MA, USA, 2003; pp. 363–376.
86. Safraz, M.; Dosdall, L.M.; Keddie, B.A. Diamondback moth host plant interactions: Implications for pest management. *Crop Prot.* **2006**, *25*, 625–639. [CrossRef]
87. Rossbach, A.; Löhr, B.; Vidal, S. Host shift to peas in the diamondback moth *Plutella xylostella* (Lepidoptera: Plutellidae) and response of its parasitoid *Diadegma mollipla* (Hymenoptera: Ichneumonidae). *Bull. Entomol. Res.* **2006**, *96*, 413–419. [CrossRef] [PubMed]
88. Silva-Torres, C.S.A.; Torres, J.B.; Barros, R. Can cruciferous agro-ecosystems grown under variable conditions influence biological control of *Plutella xylostella* (L.) (Lepidoptera: Plutellidae). *Biocontrol Sci. Technol.* **2011**, *21*, 625–641. [CrossRef]
89. Sohati, H.P. Establishment of *Cotesia vestalis* (Haliday) and *Diadromus collaris* (Grav.) Parasitoids of the Diamondback Moth *Plutella xylostella* (L.) and Assessment of the Effectiveness of *Cotesia vestalis* as a Biological Control Agent in Zambia. Ph.D. Thesis, University of Zambia, Lusaka, Zambia, 2012.
90. Mazlan, N.; Mumford, J. Insecticide use in cabbage pest management in Cameron highlands, Malaysia. *Crop Prot.* **2004**, *24*, 31–39. [CrossRef]
91. Price, L.L. Demystifying farmers' entomological and pest management knowledge: A methodology for assessing the impacts on knowledge from IPM-FFS and NES Interventions. *Agric. Hum. Values* **2001**, *18*, 153–176. [CrossRef]
92. Stadlinger, N.; Mmochi, A.J.; Dobo, S.; Glyllback, E.; Kumblad, L. Pesticide use among smallholder rice farmers in Tanzania. *Environ. Dev. Sustain.* **2011**, *13*, 641–656. [CrossRef]
93. Williamson, S. Understanding natural enemies: A review of training and information in the practical use of biological control. *Biocontrol News Inf.* **1998**, *19*, 117–126.
94. Hough, P. *The Global Politics of Pesticides: Forging Consensus from Conflicting Interests*; Earthscan Publications Ltd.: London, UK, 1998.
95. Association of Veterinary and Crop Associations of South Africa (AVCASA). *Hands off Banned Pesticides*; Media Statement; AVCASA: Midrand, South Africa, 2008.
96. Quinn, L.P.; de Vos, B.J.; Fernandes-Whaley, M.; Roos, C.; Bouwman, H.; Kylin, H.; Pieters, R.; van den Berg, J. Pesticide Use in South Africa: One of the Largest Importers of Pesticides in Africa. 2012. Available online: http://www.intechopen.com/books/pesticides-in-the-modern-world-pesticides-use-and-management/pesticide-use-in-south-africa-one-of-the-largest-importers-ofpesticides-in-africa (accessed on 5 January 2017).
97. Löhr, B.; Kfir, R. Diamond back in Africa: A review with emphasis on Biological Control. In *Improving Biocontrol of Plutella xylostella*; Kirk, A.A., Bordat, D., Eds.; Agricultural Research for Development: Montpellier, France, 2004.
98. Momanyi, C.; Löhr, B.; Gitonga, L. Biological Impact of the Exotic Parasitoid *Diadegma semiclausum* (Hellen) of diamondback moth *Plutella xylostella* (L.) in Kenya. *Biol. Control* **2006**, *38*, 254–263. [CrossRef]
99. Löhr, B.; Kfir, R. Diamondback moth *Plutella xylostella* (L.) in Africa: A review with emphasis on biological control. In Proceedings of the International Symposium, Montpellier, France, 21–24 October 2002.
100. Chidawanyika, F.; Terblanche, J.S. Costs and benefits of thermal acclimation for codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae): Implications for pest control and the sterile insect release programme. *Evol. Appl.* **2011**, *4*, 534–544. [CrossRef] [PubMed]
101. Sørensen, J.; Addison, M.; Terblanche, J.S. Mass rearing of insects for pest management: Challenges, synergies and advances from evolutionary physiology. *Crop Prot.* **2012**, *38*, 87–94. [CrossRef]
102. Overgaard, J.; Sørensen, J.G. Rapid thermal adaptation during field temperature variations in *Drosophila melanogaster*. *Cryobiology* **2008**, *56*, 159–162. [CrossRef] [PubMed]
103. Kristensen, T.N.; Hoffmann, A.A.; Overgaard, J.; Sørensen, J.G.; Hallas, R. Costs and benefits of cold acclimation in field released *Drosophila*. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 216–221. [CrossRef] [PubMed]

104. Htun, P.W.; Myint, M. Radiation induced sterility for biological control of diamondback moth *Plutella xylostella* (L.). *Int. J. Adv. Sci. Eng. Technol.* **2014**, *4*, 285–291.
105. Dyck, V.A.; Hendrichs, J.; Robinson, A.S. *Sterile Insect Technique: Principles and Practice in Area-Wide Integrated Pest Management*; Dyck, V.A., Hendrichs, J., Robinson, A.S., Eds.; Springer: Dordrecht, The Netherlands, 2005.
106. Harvey-Samuel, T.; Morrison, N.I.; Walker, A.I.; Marubbi, T.; Yao, J.; Collins, H.L.; Gorman, K.; Davies, T.G.E.; Alphey, N.; Warner, S.; et al. Pest control and resistance management through release of insects carrying a male sterile transgene. *BMC Biol.* **2015**, *13*, 49–64. [CrossRef] [PubMed]
107. Ant, T.; Koukidou, M.; Rempoulakis, P.; Gong, H.F.; Economopoulos, A.; Vontas, J.; Alphey, L. Control of the olive fruit fly using genetics-enhanced sterile insect technique. *BMC Biol.* **2012**, *10*, 51. [CrossRef] [PubMed]
108. Leftwich, P.T.; Koukidou, M.; Rempoulakis, P.; Gong, H.F.; Zacharopoulou, A.; Fu, G.; Chapman, T.; Economopoulos, A.; Vontas, J.; Alphey, L. Genetic elimination of field-cage populations of Mediterranean fruit flies. *Proc. R. Soc. Biol. Sci.* **2014**, *281*, 1792. [CrossRef] [PubMed]
109. De Valdez, M.R.W.; Nimmo, D.; Betz, J.; Gong, H.F.; James, A.A.; Alphey, L. Genetic elimination of dengue vector mosquitoes. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 4772–4775. [CrossRef] [PubMed]
110. Van Veen, S. The worldbank and pest management. In *Integrated Pest Management in the Global Arena*; Maredia, K.M., Dakouo, D., Mota-Sanchez, D., Eds.; Commonwealth Agricultural Bureau International (CABI): Wallingford, UK, 2003.
111. Gillson, L.; Dawson, T.P.; Jack, S.; McGeoch, M.A. Accommodating climate change contingencies in conservation strategy. *Trends Ecol. Evol.* **2013**, *28*, 135–142. [CrossRef] [PubMed]
112. Cook, S.M.; Khan, Z.R.; Pickett, J.A. The use of push-pull strategies in Integrated Pest Management. *Ann. Rev. Entomol.* **2007**, *52*, 375–400. [CrossRef] [PubMed]
113. Khan, R.Z.; Midega, C.A.O.; Bruce, T.J.A.; Hooper, A.M.; Pickett, J.A. Exploiting phyto-chemicals for developing a "push-pull" crop protection strategy for cereal farmers in Africa. *J. Exp. Bot.* **2010**, *10*, 1–12.