Chapter

Russian Wheat Aphid Distribution in Wheat Production Areas: Consequences of Management Practices

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Abstract

Russian wheat aphid (RWA) is an international pest on wheat and occurs in most countries where large scale wheat cultivation is practiced. Consequently, considerable efforts have been made to manage RWA globally. The two management options used currently are chemical control and breeding for deployment of resistant wheat cultivars. There are however drawbacks to both of these management practices. Chemical control has a negative impact on the environment, especially other insect groups such as predators, pollinators and decomposers. With widespread and continuous use of the same active ingredients, there is the possibility that RWA can build up resistance against these specific active ingredients. The drawback with resistance breeding is that certain RWA populations can overcome the resistance in the wheat, resulting in new biotypes virulent to the resistant wheat cultivars.

Keywords: Russian wheat aphid, *Diuraphis noxia*, wheat, *Triticum aestivum*, biotypes, insecticide resistance

1. Introduction

Establishment success and rate of spread will determine the invasive ability of a specific organism [1]. The success of an invasive species will further be determined by both abiotic and biotic factors that will influence the adaptation and spread within the geographic range of establishment [2]. Liu *et al* [3] believe that Russian wheat aphid (RWA), *Diuraphis noxia* (Kurdjumov) possesses many of the features that define a 'good invader' and as a result became a global threat to wheat production. RWA has originally spread from central Asia [4] to other major wheat (*Triticum aestivum* L.) producing countries in the world. It is considered a primary pest of dryland winter wheat in North America [5] and South Africa [6]. RWA, like other exotic aphid species, is capable of surviving at low numbers for a relatively long period and can have sudden population outbreaks in new areas [7]. The most recent record of this aphid invading a new area was in 2016 in Southern Australia and RWA is consequently considered a major threat to cereal production in Australia as well [8]. In an updated distribution model for predicting potential spread of RWA, Avila et al. [9] suggested that RWA would be able to establish in all major wheat- and barley-growing regions in New Zealand. The first record of RWA outside its original area of distribution was in South Africa in 1978. Initially the distribution was confined to the Bethlehem area in the Eastern Free State, but by 1979, the RWA had spread to other wheat-producing areas in the country [6]. The first record of RWA in the United States was in 1986 [5]. RWA invaded all the Central European countries from the south-east [10] and was first detected in the Czech Republic in 1993 [11, 12]. It was found that RWA expanded from its Mediterranean distribution range to the northwest. It seems that the expansion route has covered Serbia, Hungary and the Czech Republic [11]. Puterka et al. [13] determined that the origin of populations distributed in South Africa, Central and North America was in Turkey with an indication of random establishment by commerce rather than through migration. Zhang et al. [14], however, found evidence of long-term existence and expansion of RWA in China and speculate that RWA are not frequently transported by human agricultural activities. With the expansion of wheat fields it is possible that aphid populations may spread to areas via natural pathways such as flight or wind currents. Once established in an area RWA is very adaptable to changes in the environment. Because of its wide distribution, considerable effort has gone into developing management strategies against this global wheat pest. Currently there are two management options: breeding for deployment of resistant wheat cultivars and chemical control.

RWA-resistant cultivars were released and deployed in South Africa during 1992, and more than 70% of the wheat production area in South Africa was planted with Russian wheat aphid-resistant cultivars [15]. The durability of resistant cultivars was, however, challenged by the occurrence of RWA biotypes, first in Colorado in 2003 [16], and in South Africa in 2006 [17]. Russian wheat aphid biotypic variation was also found in Hungary [18] and Chile [19]. Since 2006, five distinct RWA biotypes have been recorded in the wheat production areas of the Eastern Free state (summer rainfall area), South Africa, RWASA2 in 2006; RWASA3 in 2009; RWASA4 in 2011 and most recently RWASA5 in 2018.

The second management option, chemical control, is also practiced in South Africa, mainly in the Western Cape (winter rainfall area) and on irrigation wheat in central and western Free State and Northern Cape. Chemical control has long term, negative impacts on the environment, especially other insect groups such as predators, pollinators, and decomposers. Hill, et al. [20] demonstrated that broad spectrum pesticide application in grain crops can lead to secondary outbreaks of pests due to alteration of natural enemy communities. The active ingredients registered for RWA control on wheat in South Africa are limited and include acetamiprid, chlorpyrifos, chlorpyrifos + cypermethrin, demeton-S-methyl, dimethoate, imidacloprid, parathion, prothiofos and thiamethoxam. With widespread and continuous use of these active ingredients, there is the possibility that RWA can build up resistance against these specific active ingredients. About 20 species in the Aphididae have evolved resistance to insecticides [21] and can be associated with detectable changes in reproductive rates [22]. Brewer and Kaltenbach [23] demonstrated that there is detectable variation in RWA insecticide susceptibility and reproductive rates after exposure to chlorpyrifos. Chlorpyrifos selection seen in wheat production may result in large scale changes in susceptibility and control failures. Russian wheat aphid variation in virulence to small grains occurs [24, 25] as well as variation in fecundity [26, 27]. There is a possibility that RWA can also evolve virulence to active ingredients in chemicals. In their recommendations for managing RWA expansion into all major grain regions of Australia Ward et al. [28] include sustainable management practices, given the somewhat indiscriminate use of insecticides to control RWA to date. They also include regular testing of field populations for evolution of insecticide resistance in their recommendations. To determine how RWA populations change over time annual monitoring was done from 2010 to 2019 in the wheat production areas of South Africa. The most recent observations is discussed here.

2. Material and methods

2.1 Survey and collection of RWA at landscape level

RWA samples were collected annually during the wheat growing season in South Africa from 2010 to 2019. All main wheat production areas within the known distribution of the RWA were sampled. The same areas were sampled each year and where possible the same fields (**Figures 1** and **2**). There are two main dryland wheat production areas in South Africa where RWA commonly occur, the Western Cape (winter rainfall area) (**Figure 1**) and the Free State (a summer rainfall area) (**Figure 2**), with irrigated wheat production areas in the Central and Western Free State and Northern Cape (**Figure 2**). Sampling sites were selected off primary or secondary roads that transected major wheat or barley production areas. Sites were 10-20 km apart with distances depending on the continuity of wheat fields. In the Western Cape an average of 32 fields were sampled (**Figure 1**) and in the Free State an average of 61 fields were sampled (**Figure 2**). Samples were collected from cultivated wheat, barley and oats as well as volunteer wheat, wild oats, rescue grass and false barley in road reserves and around cultivated fields. Infested leaves were placed in Petri dishes containing moist filter paper and stored in an icebox for transportation to the glasshouse. The number of aphids per plant, percentage plants infested, growth stage of the plants and damage on the plants were recorded. The geographical co-ordinates and elevation where the samples were collected were also captured on a GPS and all the information of each sample collected was entered into a database (Windows Office –Excel).

2.2 Establishing clone colonies of collected RWA samples

A single female aphid from each sample collected in the field was transferred to a wheat plant and caged (gauze size: 315micron) to produce a clone colony. RWA clone colonies are kept in glasshouse cubicles at night/day temperatures of 16 °C/22 °C and maintained on various wheat cultivars to avoid pre-adaptation to a specific cultivar until they multiplied sufficiently to be used for screening. Each clone colony is cultured for an average period of two to three months before screening.

2.3 Screening of clone colonies of collected RWA samples for determination of potential biotypes

The biotype of each RWA clone was determined by screening its feeding damage on 11 previously established plant resistant sources containing designated resistance genes *Dn*1 to *Dn*9 and *Dnx* and *Dny* (**Table 1**). Infestations of RWASA1 cause susceptible damage symptoms on wheat entries containing the *Dn2* and *Dn*3 gene (**Table 1**). RWASA2 cause susceptible damage symptoms on wheat entries containing *Dn*1, *Dn2*, *Dn*3, *Dn8* and *Dn*9 resistance genes (**Table 1**). RWASA3 is distinguished from RWASA2 by its added virulence to *Dn*4 and RWASA4 is distinguished from RWASA3 by its added virulence to *Dn5* (**Table 1**). RWASA5 is distinguished from RWASA4 by its added virulence to *Dn*6 and *Dn*x (**Table 1**).

Ten seeds of each plant entry were planted in a seedling tray filled with sterilized sand in a randomized complete block design with four replications for each biotype

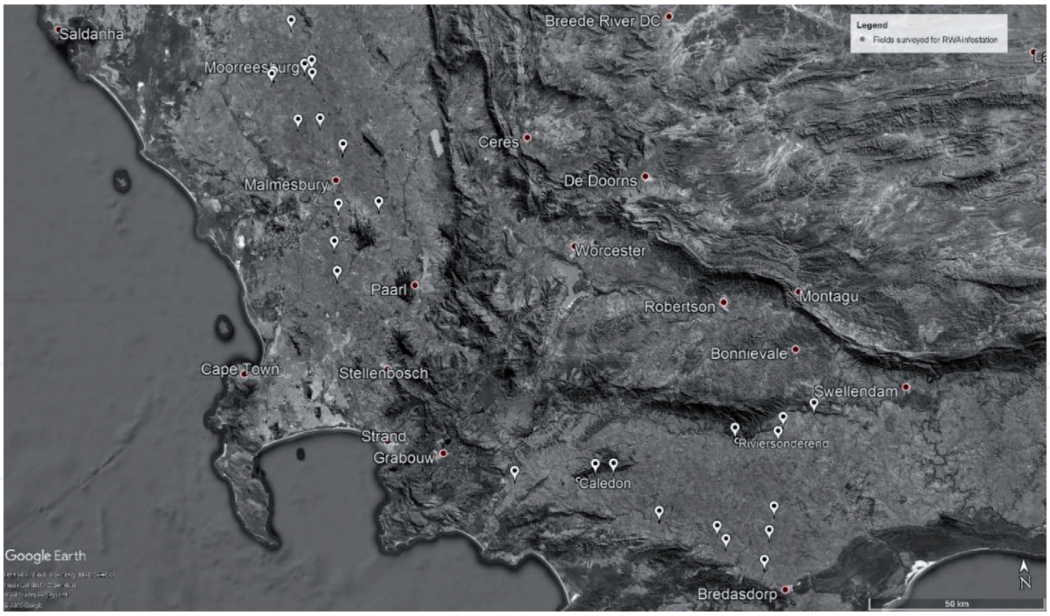

Figure 1.
Sampling sites for Russian wheat aphid (RWA) in the Western cape (winter rainfall area), South Africa from 2010 to 2019.

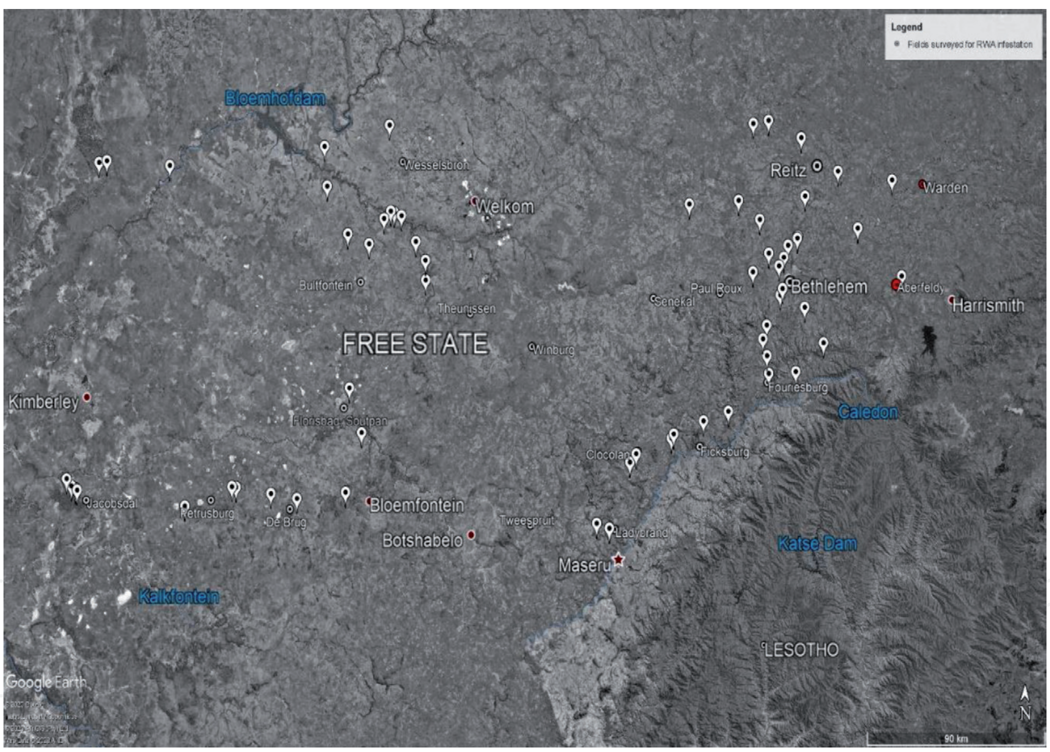

Figure 2.
Sampling sites for Russian wheat aphid (RWA) in the Free State (summer rainfall area), South Africa from 2010 to 2019.

determination. Plant entries were randomly assigned to rows and were separated by border rows planted with RWA susceptible Tugela. Plants were kept in glasshouse cubicles at night/day temperatures of 16 °C/22 °C, natural light. Immediately after planting, the seedling trays were placed in gauze (315micron) cages to avoid contamination by secondary aphids. Plants were infested at the two-leaf stage with collected RWA clone colonies. Plants were rated with a ten-point damage rating scale, which included leaf chlorosis and leaf rolling [29]. A score from 1–4 describes leaf chlorosis, 5–6 striping on the leaves and 7–10 rolling. Once the susceptible wheat Tugela showed susceptible damage symptoms, all plants were rated. RWA biotypes were classified

Wheat genotype	*Dn* R gene gengene	RWASA1	RWASA2	RWASA3	RWASA4	RWASA5
CO03797	*Dn1*	R	S	S	S	S
CO03804	*Dn2*	S	S	S	S	S
CO03811	*Dn3*	S	S	S	S	S
Yumar	*Dn4*	R	R	S	S	S
CO9500043	*Dn5*	R	R	R	S	S
CO960223	*Dn6*	R	R	R	R	S
94 M370	*Dn7*	R	R	R	R	R
Karee-*Dn*8	*Dn8*	R	S	S	S	S
Betta-*Dn*9	*Dn9*	R	S	S	S	S
PI586955	*Dnx*	R	R	R	R	S
Stanton	*Dny*	R	R	S	S	S

Table 1.
Comparison of plant reaction of the five Diuraphis noxia *biotypes identified in South Africa.*

by using damage ratings for each plant entry where the plant was considered resistant (R) if the damage rating was 1–6.5 and susceptible (S) if the damage rating was above 6.5–10. Each clone was given a biotype designation based on the differential virulence profile to the *Dn*1 to *Dn9* and Dnx and Dny resistance genes (**Table 1**).

Biotype (clones) groups across all plant differentials were analyzed using a two-way (clone, plant entry) analysis of variance (ANOVA). Mean damage rate entries with significant ($P < 0.05$) clone-by-plant interactions were separated by Fisher's protected least significant difference (LSD) test at the 5% level (SAS Institute 2003).

3. Results and discussion

Representative samples of five RWA biotypes were collected in the different wheat production areas in South Africa, with a range of different climatic conditions and different host plants from 2010 to 2019 (**Figures 1** and **2**). The number of samples collected in a specific area varied depending on the area planted with wheat or barley or the availability of alternative hosts and the level of infestation. An average of 32 fields were sampled in the Western Cape (**Figure 1**) and 61 in the Free State (**Figure 2**). Environmental conditions, including temperature, humidity, rainfall, soil type and availability of host plants play an important role in the population increase and distribution of different RWA biotypes. Because these variables change from year to year and between different areas, the distribution of RWA biotypes will vary over years and between different geographical areas.

Analysis of the main effects of damage rating for the five Russian wheat aphid biotype colonies indicated a significant clone ($F = 117.48$; $df = 3$; $P < 0.0001$), plant entry ($F = 133.59$; $df = 11$; $P < 0.0001$) and clone-by-plant entry interaction ($F = 12.82$; $df = 33$; $P < 0.0001$), suggesting that the plant entries responded differently to the different aphid clones. Biotypes are identified by the distinct feeding damage responses they produce on wheat carrying different RWA resistance genes from *Dn*1 to *Dn*9 [30]. Infestations of RWASA1 caused susceptible damage symptoms on the wheat entry containing the *Dn2* and *Dn*3 gene (**Table 1**). RWASA2 caused susceptible damage symptoms on wheat entries containing *Dn*1, *Dn2*, *Dn*3, *Dn8* and *Dn*9 resistance genes (**Table 1**). RWASA3 is distinguished from RWASA2 by its added virulence to *Dn*4 and RWASA4 is distinguished from RWASA3 by its added virulence to *Dn5* (**Table 1**). RWASA5 was the most virulent biotype in South Africa with susceptible responses to ten plant differentials containing ten different *Dn* genes (**Table 1**). Randolph et al. [31] found the American RWA2 to be the most virulent strain tested with susceptible responses to 12 plant differentials.

The concentration of RWA biotypes occurred mainly in the Eastern Free State with very few wheat fields infested with RWASA1 (original biotype, reported in 1978). RWASA1 occurred mainly in the Western Free State and Northern Cape. Since 2006, five distinct RWA biotypes have been recorded in the wheat production areas of the Eastern Free State, RWASA2 in 2006; RWASA3 in 2009; RWASA4 in 2011 and RWASA5 in 2018. The populations of RWA biotypes fluctuated over the years with RWASA2 being the dominant biotype from 2010 to 2011, RWASA3 dominating from 2012 to 2013 and RWASA4 from 2014 to 2016 (**Figure 3**). During the 2018 season RWASA5, was recorded for the first time on 8 wheat fields in the Lindley, Reitz and Danielsrus areas in the Eastern Free State. During 2019 this biotype had increased and spread to other areas of the Eastern Free State and was recorded on 12 wheat fields in the Eastern Free State. This biotype was dominant from 2018 to 2019 (**Figure 3**). Merrill et al. [32] found, in a general survey of aphid mixtures for virulence to resistant Yumar (with *Dn*4 gene) in Colorado from 2004 to 2008, that *Dn*4 virulence increased from 82% in 2005 to 98% in 2008. When a new RWA biotype appear, this new biotype seem to be able to outcompete the previous biotypes in the area and displace the other biotypes. Puterka et al. [33] found, in an area-wide study in the USA during 2005, that RWA2 almost completely displaced the original biotype. A survey from 2010 to 2013 revealed a change in biotypic diversity of RWA populations in the United States, with RWA 1,6 and 8 across regions showing high percentages during 2011 (64–80%) and 2013 (69–90%) [34]. In South Africa RWA biotype with added virulence to genes used in resistant wheat cultivars were recorded every 2 to 3 years in the Eastern Free State where RWA resistant wheat cultivars were commonly deployed. These newly recorded RWA biotypes became the dominant biotype in these areas until a more virulent RWA biotype was recorded (**Figure 3**). The most recently recorded biotype during 2018, RWASA5, is virulent against all known *Dn* genes used in wheat except *Dn*7 (94 M370) (**Table 1**).

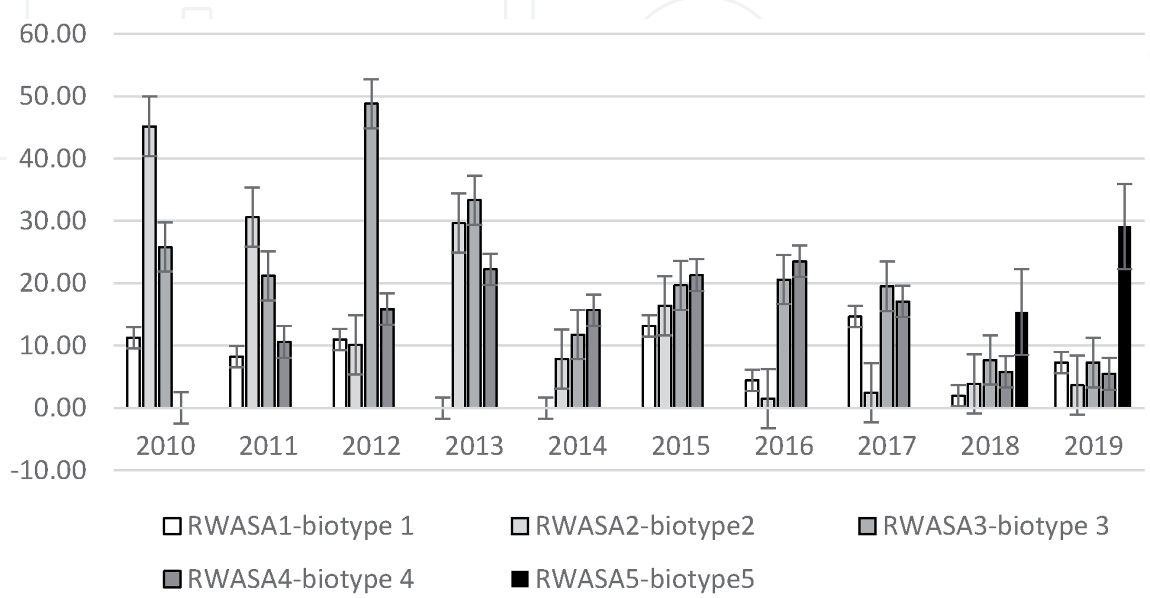

Figure 3.
Russian wheat aphid (RWA) SA biotype distribution in the Free State, South Africa (summer rainfall area) from 2010 to 2019 (average fields sampled: 61).

With the increase and spread of more virulent RWA biotypes the use of insecticides may again become the main management option in these areas. Merrill et al. [35] found that even though resistant wheat cultivars historically provided excellent management of RWA on wheat crops in Colorado, the increase of new RWA biotypes resulted in all commercially available winter wheat cultivars being susceptible to RWA feeding damage and associated yield losses. This led to insecticides once again becoming the main management tactic used on Colorado wheat [35]. In the Western Cape, where chemical control is the most common control measure for RWA, RWASA1 remained the only biotype and the biotype diversity seen in the Eastern Free State was not experienced in this area. There was however, an increase in RWASA1 incidence in the Western Cape from between 30 to 60% fields infested from 2010 to 2016 to between 70 to 100% fields infested with RWA from 2017 to 2019 on the fields that were annually surveyed (**Figure 4**). In a survey of farmers in the Western Cape during the 2017 wheat production season 75% of the respondents observed RWA on their crops [36]. All these farmers use chemical control, in the form of preventative spray, to control RWA, because it is cheap and effective [36]. The fact that RWASA1 became more widespread in the Western Cape and that in some cases live populations were collected in fields recently sprayed with insecticides may indicate insecticide resistance. The active ingredients registered for RWA control on wheat in South Africa are limited and include acetamiprid, chlorpyrifos, chlorpyrifos + cypermethrin, demeton-S-methyl, dimethoate, imidacloprid, parathion, prothiofos and thiamethoxam. The most common active ingredients used by producers in the Western Cape are chlorpyrifos, dimethoate, imidacloprid and thiametoxam (Mr K. Naicker, Cape RnD, Meridian Agritech). In the Western USA, chlorpyrifos was the predominantly used insecticide, with area-wide treatment of wheat acreage in specific localities [37]. Puterka et al. [13] detected genetic variation and potential for biotypic diversity in RWA among world-wide collections of RWA from countries in Eurasia, South Africa and the United States in 1990. This variation in other traits may be indictors of adaptations, which could confer RWA resistance to chlorpyrifos [23]. Brewer and Kaltenbach [23] demonstrated that variation in RWA susceptibility to chlorpyrifos and associated reproductive rates occur in the small grains growing region of the USA. Furthermore, approximately 20 species in the Aphididae have evolved resistance to insecticides [21] that can be

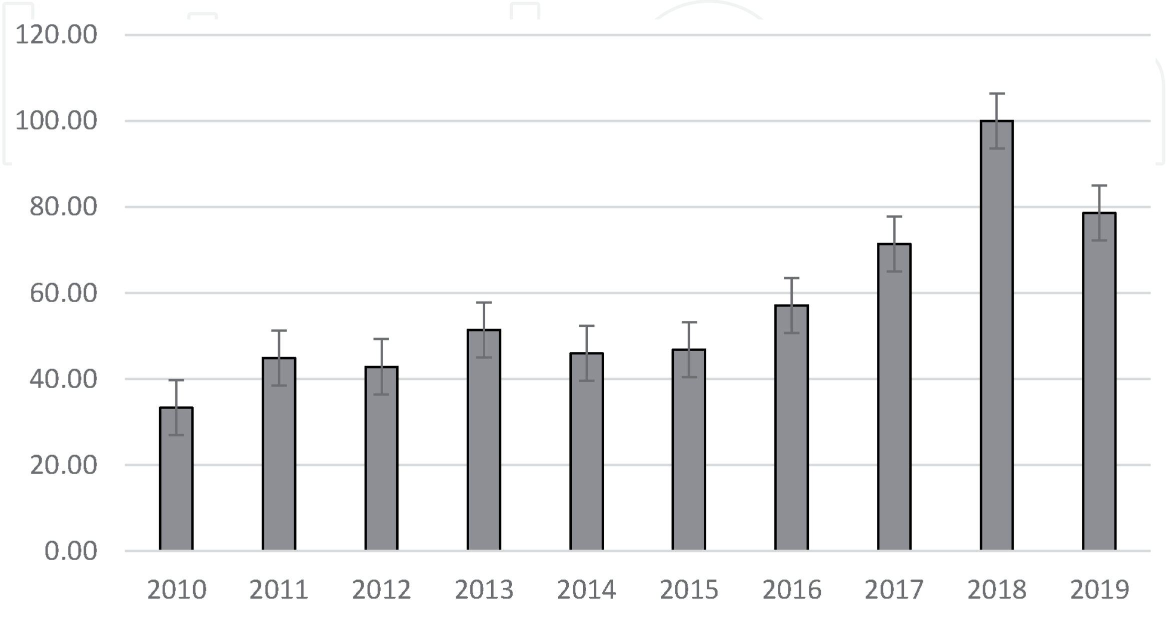

Figure 4.
Percentage of wheat fields surveyed in the Western cape, (winter rainfall area), South Africa, infested with Russian wheat aphid (RWA) SA biotype1 (average fields sampled: 32).

associated with detectable changes in reproductive rates [22]. In South Africa RWA showed considerable biotypic adaptation and change in reproductive rate to resistant wheat [25, 27, 38], resulting in five RWA biotypes occurring in wheat production areas where RWA resistant wheat were deployed in the Eastern Free State. This may be an indication that RWA in South Africa have the adaptive ability to develop resistance to active ingredients of insecticides used to control them in the Western Cape. Large-scale changes in susceptibility were detected in other aphids in which consistent and severe selection pressure occurred [21]. Brewer and Kaltenbach [23] stated that even though control failure problems have not been reported, periodic assessment of RWA populations of field derivation is necessary. Ward et al. [28] also recommend regular testing of field populations to understand if insecticide resistance is likely to evolve in Australia. According to Brewer and Elliott [39] better understanding of the mediating effects of host plant and habitat manipulations may accelerate our ability to plan cereal production systems with improved ability to suppress cereal aphids, including future invading species.

4. Conclusion

Given the invasive ability, evolutionary adaptability to changing conditions, virulence, and fecundity of RWA, it remains a threat to global wheat production and wheat cultivation. RWA remain present in all the wheat production areas of South Africa and these populations are becoming more virulent as indicated by the spread of the recently recorded biotype, RWASA5, in the Eastern Free State. Management practices in different regions of South Africa may cause increased virulence in RWA populations. Based on these observations testing of field populations to understand if insecticide resistance is evolving in RWA populations in the Western Cape is warranted. It is important that future management practices focus on sustainability instead of the indiscriminate use of insecticides globally to control RWA to date. Increasing diversity in fields through undersowing, reduced tillage, intercropping and incorporation of cover crops will be an effective start to sustainable management practices. Vegetation strips have favorable microclimate for survival of generalist predators, and alternative prey and resources during winter, resulting in higher densities of generalist predators in cereal fields [40, 41]. This together with minimal use of insecticides, only when necessary, will increase the insects providing ecosystem services and predators, parasitoids and pathogens that will keep RWA populations and economical damage low. Management approaches against cereal aphid invasions differ depending on aphid ecology, specific system influences, and local management practices [42]. Any practice based on aphid population monitoring that facilitates threshold-based insecticide use will be effective across agroecosystems, with area-wide management systems being most appropriate to large-scale cereal production systems.

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Conflict of interest

The author declare no conflict of interest.

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