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Areawide Pest Management of Cereal Aphids in Dryland Wheat Systems of the Great Plains, USA

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Introduction: Description of the Problem and Need for an Areawide Pest Management Approach

In the Great Plains of the USA from Wyoming to Texas, dryland winter wheat either is regularly grown continuously or is followed by a year of fallow in semi-arid locales (Royer and Krenzer, 2000). It has been well documented that these continuous monocultures can, over time, lead to increased levels of all types of pests (i.e. insects, diseases and weeds) (Andow, 1983, 1991; Vandermeer, 1989; Cook and Veseth, 1990; Elliott *et al.*, 1998a; Way, 1998; Ahern and Brewer, 2002; Boyles *et al.*, 2004; Brewer and Elliott, 2004; Men *et al.*, 2004). Relative to insect pests, the ephemeral nature of insect host resources in these monoculture systems is assumed to curtail the efficiency of natural enemies, leading to increased pest pressure and reduced yields (Booij and Noorlander, 1992; Tscharntke *et al.*, 2005; Clough *et al.*, 2007).

From an ecological standpoint, the absence of habitats that support natural enemies in these monoculture agricultural systems are considered a primary reason why populations of aphids such as the greenbug (GB, *Schizaphis graminum*) and the Russian wheat aphid (RWA, *Diuraphis noxia*) increase above economic injury levels (EILs) (Elliott *et al.*, 1998b, 2002a; French and Elliott, 1990a; Brewer *et al.*, 2001; French *et al.*, 2001a; Giles *et al.*, 2003; Brewer and Elliott, 2004). Economic losses associated with both GB and RWA average US$150 million annually across the Great Plains of the USA (Webster, 1995; Morrison and Pears, 1998).

Management of aphids in winter wheat has been addressed by the use of resistant cultivars (GB- and RWA-resistant wheat); however, the adoption of these

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cultivars has been limited. In most dryland systems, the primary management tool for suppression of severe aphid populations is the use of costly broad-spectrum insecticides, which can lead to a cycle of pest resurgence, additional applications and increased risk of insecticide resistance (Trumper and Holt, 1998; Wilson *et al.*, 1999; Wilde *et al.*, 2001; Kfir, 2002; Elzen and Hardee, 2003; Peairs, 2006).

Additionally, producers continue to be concerned with increasing weed and disease problems in monoculture wheat production systems and the costs associated with managing these pests (Keenan *et al.*, 2007a, b). All together, these difficult pest management issues have led some producers to move toward more diverse agricultural systems in an effort to reduce pest pressure, minimize inputs and risks and increase net returns (Peterson and Westfall, 1994, 2004; Lyon and Baltensperger, 1995; Dhuyvetter *et al.*, 1996; Brewer and Elliott, 2004; Keenan *et al.*, 2007a, b).

Over the past decade, changes in the US Farm Programme, primarily in the form of reduced crop price supports, have allowed producers to be more flexible in their choice of crops. These reduced price supports demand that producers incorporate efficient pest management tactics. For the typical dryland winter wheat producer in the Great Plains whose profit margin is often very low, it is essential to use innovative IPM approaches that reduce input costs, optimize production and net profits, conserve soil and non-target organisms and reduce risks to humans and livestock (Helms *et al.*, 1987; Sotherton *et al.*, 1989).

Because of the Food Quality Protection Act, inexpensive insecticides traditionally used for aphid control in wheat may not be available in the future; therefore, wheat producers will have to utilize more ecologically based management approaches in this low-profit margin crop. Because of the costs and environmental concerns associated with insecticide use in these wheat systems in the Great Plains, an areawide pest management (AWPM) strategy may be the only justifiable approach in this region.

Knipling (1980) advocated regional, or areawide, population management of pests like GB and RWA that are dispersive and ubiquitous in agricultural landscapes (Elliott *et al.*, 1998a; Vialatte *et al.*, 2006). It is theorized that if a management approach is used over a broad agricultural landscape, pests such as GB and RWA can be effectively managed by 'environmentally benign' approaches (Knipling, 1980). For GB and RWA, which continue to reach economic levels in the traditional wheat-intensive, dryland winter wheat systems, a suitable alternative management strategy should involve the utilization of suppressive forces within cropping systems and across the agricultural landscape.

One major assumption of the Cereal Aphid AWPM project was that both GB and RWA could be maintained below economic levels across a broad area when both available resistant cultivars and diversified cropping systems were utilized within a landscape. Theoretically, the combined effect of reduced aphid numbers over a broad area via resistance and the increased effectiveness of conserved biological control agents would greatly reduce the economic impact of these pests (Holtzer *et al.*, 1996; Peairs *et al.*, 2005).

Fortunately, research on aphid management in wheat systems in the Great Plains supported our assumption that diversified wheat-cropping systems support non-economic populations of aphids and help to conserve aphid predators and parasitoids (Parajulee *et al.*, 1997; Elliott *et al.*, 1998a, 2002a, b; Brewer *et al.*, 2001; French *et al.*, 2001; Brewer and Elliott, 2004). In these studies, inclusion or rotation of crops into wheat systems such as canola, millet, sorghum, clover, lucerne, cotton and sunflowers provided the diverse landscape structure and resources required to conserve aphid predators and parasitoids in wheat (Elliott *et al.*, 1994a, b, c, 1998a, 1999, 2002a; French and Elliott, 1999a, b; French *et al.*, 1999a). Clearly, the strong evidence that diversification of a farming landscape conserves natural enemies justifies the evaluation of an AWPM programme for aphids in winter wheat.

The cereal aphid AWPM programme in wheat was a multifaceted approach that included detailed sociological and economic evaluations, experimental and demonstration pest studies and a comprehensive education/outreach programme that is still ongoing. In this chapter, much of the discussion will focus on the methodology and findings from the regionwide demonstration sites. Demonstration sites, which included monoculture (continuous wheat or wheat–fallow) systems and diversified wheat production systems, were set up at the farm landscape scale and paired throughout the Great Plains region. Ultimately, economic findings from these demonstration farms will support the justification for increasing adoption of diversified farming systems. However, data on aphid, natural enemy and weed densities at paired demonstration sites provide evidence as to the mechanisms involved for AWPM of cereal aphids in wheat.

Significance of the Pest Management Problem

Dryland wheat monocultures (either continuous or wheat–fallow) dominate production landscapes in the Great Plains (see Fig. 19.1), but often lead to increased pest problems. Producers in this region are regularly faced with aphid pressure in their wheat fields, the most common and damaging of which are the greenbug and Russian wheat aphid (Kelsey and Mariger, 2002; Giles *et al.*, 2003; Mornhinweg *et al.*, 2006; Keenan *et al.*, 2007a, b).

The greenbug is considered the key pest of wheat in much of Oklahoma, Texas and Kansas because of its frequent occurrence and potential for severe damage. In the absence of natural enemies, greenbugs are capable of rapidly reproducing in these warmer locations of the Great Plains, damaging or killing wheat plants and significantly reducing yields (Kieckhefer and Kantack, 1988; Webster, 1995; Kindler *et al.*, 2002, 2003; Giles *et al.*, 2003). The GB occurs sporadically throughout Colorado and Nebraska, and will occasionally exceed EILs. In each state of the Great Plains, GB outbreaks occur somewhere every year. Less frequent regional GB outbreaks occur every 5–10 years and result in greatly reduced yields and heavy insecticide use. The combined economic losses associated with insecticide costs and yield reductions caused by the GB alone have not been calculated for the entire region, but estimates for Oklahoma, where yearly losses in wheat range from US$0.5 to 135 million, illustrate the extent of the problem (Webster, 1995). Extrapolating these losses to the entire Great Plains suggests that GB cause annual losses of US$1.5–405 million.

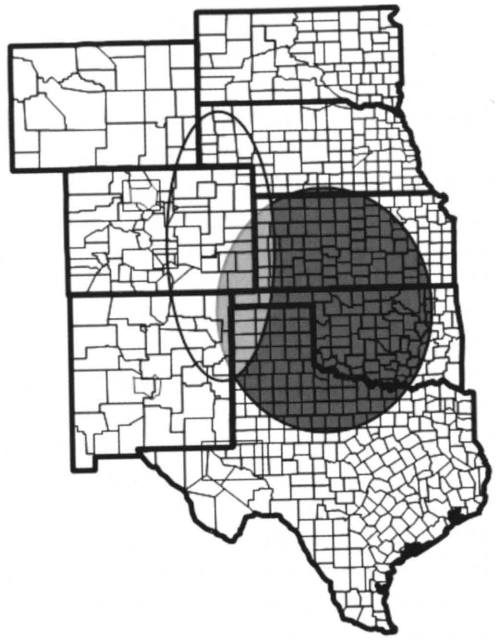

Fig. 19.1. Areas of the Great Plains, USA where RWA and GB are key pests of wheat and other cereals. Dark, GB; white, RWA; grey, the area where both species are severe pests.

Russian wheat aphid continues to be a major problem in the west-central more arid portions of the Great Plains (see Fig. 19.1) and is often the main management focus for wheat producers in this region (Archer *et al.*, 1992, 1998; Peairs, 2006; Keenan *et al.*, 2007a, b). Total economic losses associated with the RWA are estimated to have exceeded US$1.2 billion since its invasion into the USA in 1986. Seventy per cent of these losses have occurred in Texas, Kansas, Oklahoma, Colorado, Nebraska and Wyoming (Elliott *et al.*, 1998a; Morrison and Peairs, 1998).

Limitations and problems associated with current management approaches

Suppression of GB and RWA in the Great Plains has historically relied on curative insecticide use. Resistant wheat cultivars have also been used in some areas where well-adapted varieties have been developed. However, during widespread severe aphid outbreaks, insecticides are applied to prevent crop losses and are often economically justifiable (Crop Profile for wheat in Kansas, 1999; Smith and Anisco, 2000; Crop Profile for wheat in Oklahoma, 2005; NASS, 2005).

During these outbreaks, many fields are treated with compounds that are highly toxic to natural enemies and have been targeted for review by the Food Quality Protection Act (FQPA): chlorpyrifos, dimethoate and methyl parathion (Crop Profile for wheat in Kansas, 1999; Smith and Anisco, 2000; Smolen and Cuperus, 2000; Crop

Profile for wheat in Oklahoma, 2005; NASS, 2005); compounds such as disulfoton and ethyl parathion have recently lost wheat registrations.

During the course of most years, GB populations often remain near or below EILs throughout the region (Giles *et al.*, 2003). However, fields can occasionally be found where GB populations are high enough to kill most plants. These situations are usually localized in fields where natural enemies are absent. High RWA populations are a chronic problem in the more arid wheat-growing areas of the region (see Fig. 19.1), but sporadic throughout most of the Great Plains. Insecticides are the only option to control high RWA populations in fields planted to susceptible cultivars, as infestations can quickly grow and destroy entire fields.

Although severe widespread infestations in this region of the USA are infrequent, these outbreaks have significantly influenced how wheat producers perceive the importance of aphids and approach management. The results from surveys and focus groups conducted to determine producer IPM priorities in wheat (Smolen and Cuperus, 2000; Kelsey and Mariger, 2002; Keenan *et al.*, 2007a, b) indicated that a majority of producers in this region considered aphids a serious to very serious problem. This perception of a potentially serious problem does occasionally lead to an over-reaction to a marginal situation by risk-averse producers.

During non-outbreak years, many acres of wheat have been sprayed to 'protect' fields as aphid populations quickly approach or exceed economic thresholds (ETs) (Giles *et al.*, 2003; NASS, 2005). An important example of this risk-averse aphid management approach was documented in Oklahoma. During the 1995/1996 growing season, most greenbug populations in Oklahoma were below EILs; however, over 800,000 acres (320,000 ha, ~US$10 million in costs) were treated with insecticides to 'protect' wheat yields (Crop Profile for wheat in Oklahoma, 2005; NASS, 2005, 2006). The 1995/1996 field season in Oklahoma reinforced findings from several studies which determined that, when greenbug control efforts were geared to protect wheat grain yields independent of economic considerations, losses were closely tied to insecticide costs (Starks and Burton, 1977; Patrick and Boring, 1990; Peairs, 1990; Massey, 1993; Webster, 1995; Giles *et al.*, 2003; Royer *et al.*, 2005).

Because profit margins of dryland wheat production in the Great Plains are very small, the net benefits of regularly suppressing GB and RWA with chemical insecticides are economically questionable. For example, the yield of dryland wheat in Colorado averages 31 bushels per acre (NASS, 1996), and with the price of wheat at US$3.00 (per bushel), the net return is approximately US$25 per acre. If a producer utilizes 1000 acres (400 ha) of a 2000-acre (800 ha) farm in wheat–fallow production, the annual net income would be estimated at US$25,000. If the producer applied just one insecticide treatment at US$11 per acre, annual income would be reduced by 44%. After a single insecticide application, there is little money left to suppress other pest problems if they develop. The common approach of producers to 'protect' wheat fields from aphids with insecticides without adequate knowledge of GB or RWA density seems illogical, but this tactic is often based on the belief that accurate sampling is too expensive and on-farm risks are reduced with the treatment. Clearly, risks are unknown; however, new, highly efficient sampling plans are now available that allow for cost-effective sampling and decision making in wheat production systems (Royer *et al.*, 2007).

Despite cost concerns in dryland wheat systems, insecticides continue to be used regularly throughout the Great Plains to manage GB and RWA. The risk-averse nature of producers in this often harsh region leads to management decisions that are not focused on optimizing economic returns or other potential negative consequences of unjustified insecticide applications (Keenan *et al.*, 2007a, b). Because aphid populations in any given wheat field in the Great Plains are often below the EIL (Giles *et al.*, 2003), this 'protect' approach is likely to result in a significant waste of money. Reliance on insecticides for aphid suppression in many dryland wheat production systems of the Great Plains, without government price supports or high wheat prices, is not economically sustainable. Additionally, this over-reliance on and misuse of insecticides can significantly impact biological control and has led to other problems, including the development of greenbug populations that are resistant to compounds used for control in wheat and concerns about the conservation of migratory birds (Klass, 1982; Grue *et al.*, 1988; Shotkoski *et al.*, 1990; Flickinger *et al.*, 1991; Sloderbeck *et al.*, 1991; Brewer and Kaltenbach, 1995; Wilde *et al.*, 2001).

Despite significant research efforts, winter wheat producers in this region have at their disposal only a few available greenbug-resistant cultivars (Porter *et al.*, 1997). TAM-110 (with the *Gb3* resistance gene) confers resistance to the most abundant greenbug biotypes C, I and E (Porter *et al.*, 1997; Lazar *et al.*, 1998). An Oklahoma-adapted, general-use variety ('OKField') with *Gb3* has been available since the autumn of 2005, but does not perform well in the typical warm soils of Oklahoma or when wheat soilborne and/or spindle streak mosaic viruses are present. TAM-110 is recommended for production in drier climates (e.g. the High Plains) because it is susceptible to leaf rust and therefore is not planted in a widespread fashion across this region (Porter *et al.*, 1997).

The most significant advancement towards management of the RWA was the release of 'Halt', 'Yumar', 'Prairie Red' and 'Prowers 99', which have been followed by several other RWA-resistant cultivars. These cultivars, with the *Dn4* resistance gene, provide protection against RWA biotype 1, but are damaged by the recently described RWA biotype 2 (Peairs, 2006; Wilde and Smith, 2006). To date, there have been no resistant varieties developed with resistance to RWA biotype 2. It is important to note that GB- and RWA-resistant wheat is not immune to infestation, and damage can occur when aphid levels are extremely high; however, resistant cultivars can withstand considerably more feeding than susceptible cultivars (Quick *et al.*, 1996; Lazar *et al.*, 1998; Kindler *et al.*, 2002; Haley *et al.*, 2004). These resistant cultivars are, however, still susceptible to aphids such as *R. padi* (BCOA), which can significantly reduce forage and grain yields (Pike and Schaffner, 1985; Riedell and Kieckhefer, 1995; Riedell *et al.*, 1999; K.L. Giles unpublished data).

Native natural enemies have been shown to play an important role in regulating GB populations in wheat in the Great Plains, often eliminating the need for insecticides (Kring *et al.*, 1985; Giles *et al.*, 2003). Native natural enemies, however, had little impact on the RWA after its introduction, resulting in a multi-year, multi-state classical biological control programme initiated by the USDA to release several exotic parasitoids in the western USA (Meyer and Peairs, 1989; Michels and Whitaker-Deerberg, 1993; Wraight *et al.*, 1993; Prokrym *et al.*, 1994; Elliott *et al.*, 1995; Pike and Stary, 1995; Pike *et al.*, 1996; Brewer *et al.*, 1998a, b).

Subsequent studies demonstrated that these organisms, along with indigenous natural enemies, are usually insufficient to prevent economic damage but are a component of natural suppression of RWA throughout the region (Brewer *et al.*, 1998a, b, 1999, 2001; Michels *et al.*, 2001; Noma *et al.*, 2005; Hein, 2006). Interestingly, wheat cultivars with aphid-resistant genes have been shown to have little to no effect on parasitoids and Coccinellidae predators (Fuentes-Granados *et al.*, 2001; Giles *et al.*, 2005). These tritrophic evaluations indicate that the beneficial effects of resistance and biological control could be synergistic (Boethel and Eikenberry, 1986; Brewer and Elliott, 2004).

Even though effective IPM tools have been developed (presence/absence sampling, resistant cultivars and conservation of biological control) in the Great Plains, many growers in this area are not aware that non-chemical alternatives for aphid control in wheat can be incorporated into their production systems (Keenan *et al.*, 2007a, b). Continuing aphid problems associated with monoculture wheat systems in the Great Plains, and the resulting reliance on insecticides for GB and RWA control, highlight the urgency for development of alternative IPM systems.

Description of the Cereal Aphid Areawide Pest Management Programme in Wheat

According to Keenan *et al.* (2007a, b), a handful of growers in the Great Plains are well aware of the problems associated with traditional management of aphids in continuous or wheat–fallow monocultures. These growers utilize resistant and susceptible wheat cultivars within intensive crop rotations to reduce pest abundance (insect, disease and weeds), conserve natural enemies and conserve moisture in dryland cropping systems. These on-farm examples provide the evidence and justification for the cereal aphid areawide project, which aimed to conserve and stabilize biological control agent populations and reduce yield loss in both resistant and susceptible wheat cultivars within and among farming systems. The maximum impact of a programme based on these technologies will be achieved when it is implemented over broad geographical areas.

The main goal of this programme was to integrate effective non-chemical pest management tactics within a farm-level production setting to prevent economic GB and RWA infestations from occurring. The entire programme included detailed sociological and economic evaluations, experimental and demonstration studies, remote sensing and simulation modelling, and a comprehensive education/outreach programme that is still ongoing. As previously discussed, we will focus on the methodology and findings from the region-wide demonstration sites. These demonstration sites, which included monoculture and diversified wheat systems, were paired throughout the states involved in this study.

Ultimately, the economic findings from these demonstration farms will provide support for adoption of diversified farming systems. The data on aphid, natural enemy and weed densities at paired demonstration sites provide evidence as to the dynamics of pest systems at the farm landscape scale. The individual farm and surrounding agricultural landscape are appropriate spatial scales at which to test the programme. From a logistical and economic standpoint, individual farms were chosen as the most practical spatial unit for evaluation and implementation of IPM tactics.

At the completion of the project we hope to provide an IPM package to wheat producers in the Great Plains that will reduce yield losses caused by aphid pests and that will lower management input costs in wheat and other crops attacked by aphids. Suppression would be accomplished by incorporating host plant resistance when appropriate and the impact of biological control conserved within a diversified system. One of our main assertions was that biological control would be enhanced in diversified cropping systems. Testing this approach on monoculture and diversified farming systems over four consecutive growing seasons was one of the main objectives of the cereal aphid areawide project.

The AWPM programme and co-occurring pests

Because pests often interact at spatial scales larger than individual fields, the effect of diversifying traditional wheat farming systems in the Great Plains on non-target pests must be considered. For example, aphid pests such as bird-cherry oat aphid (BCOA) infrequently reach pest status, but are often at low levels and usually cause little damage to wheat in the region (Riedell and Kieckhefer, 1995; Riedell *et al.*, 1999; K.L. Giles unpublished data).

We expected the impact of diversification to further reduce damage by BCOA and other minor aphid pests. The wheat stem sawfly, *Cephus cinctus*, is restricted as a pest to the northern edge of the region evaluated for this study. Host plant resistance and cultural practices are the main tactics used to control *C. cinctus*. In wheat production systems where tillage is reduced, increased sawfly populations are more likely; however, diversity would be expected to reduce its significance as a pest (Hatchet *et al.*, 1987). Armyworms and cutworms are sporadic pests of small grains in the region, and we anticipated that diversified cropping systems would have little effect on these organisms.

Other arthropod pests such as the wheat curl mite, which transmits wheat streak mosaic virus (WSMV), were considered. WSMV is the most serious cereal disease in the western Great Plains (Brakke, 1987), with widespread epiphytotics occurring every few years. The WSMV situation is complicated by the recent prevalence of High Plains virus (HPV), which is also damaging to wheat and probably interacts with WSMV to impact wheat more severely.

Management of the disease involves managing the mite vector. These mites can survive only on green plant material; therefore, management must focus on reducing mite populations during the period when it must survive between wheat harvest and the subsequent wheat crop (i.e. green bridge period). Volunteer wheat is the most important green bridge host for the mite and virus. Crop diversification with crops that are not hosts to the mites will probably reduce the incidence of the mite and virus unless volunteer wheat is not controlled well in these crops. However, crop rotation with host crops (e.g. maize, foxtail millet) needs to be considered with caution. Delayed planting also reduces the risk of serious WSMV. WSMV/HPV disease was monitored during the programme.

Additionally, producers continue to be concerned with increasing weed problems in monoculture systems and the costs associated with managing these organisms (Boyles *et al.*, 2004; Keenan *et al.*, 2007a, b). Jointed goatgrass, downy brome, volunteer rye and volunteer wheat constitute the most serious weed threats to winter wheat production in the Great Plains. Annual grass weeds reduce wheat yields and cost wheat producers about US$20 million annually in Colorado (Anon., 1990); similar losses occur elsewhere in the Great Plains. Widespread adoption of reduced tillage farming has aided the establishment and spread of annual grass weeds (Anon., 1991).

Winter annual grass control in continuous and wheat–fallow systems is extremely difficult, because the life cycle of grasses is synchronized with that of winter wheat, and few cost-effective available herbicides provide selective grass control in winter wheat. Kochia (*Kochia scoparia*) is the most common spring-germinating annual weed in winter wheat in the Great Plains and has rapidly developed resistance to the primary control strategy (sulphonylurea herbicides). Surveys indicate that over 50% of kochia in dryland sites is herbicide resistant (Westra and Amato, 1995).

Diversification of farming systems by rotation of a second crop will allow for cheaper, less chemically intensive control of grassy weeds and kochia (Lyon and Baltensperger, 1995; Westra and Amato, 1995). Rotation allows for grassy weed germination in a non-grass crop that is highly competitive and allows for use of herbicides that will not damage the non-grass crop. More effective kochia control is possible in the rotational crop by using alternative herbicides (Tonks and Westra, 1997). Because of selective and targeted herbicide use, we anticipate significant reductions of weeds in rotational diversified systems.

Anticipated benefits of Areawide Pest Management

The GB and RWA thrive in the monoculture wheat systems, and other pest problems in general have increased in this system (Way, 1988; Andow, 1991; Lyon and Baltensperger, 1995; Holtzer *et al.*, 1996). Diversification of crops within a production system can have several desirable consequences for farmers. One of the well-documented benefits of diversification is lower insect pest pressure, and evidence is accumulating that diversifying cropping systems increase and support natural enemy populations, and consequently increase the effectiveness of biological control (Parajulee and Slosser, 1999; Guerena and Sullivan, 2003; Brewer and Elliott, 2004). Furthermore, when aphid-resistant wheat cultivars are incorporated into a diversified system, the combined effect of natural enemies and host plant resistance can be interactive, resulting in a reduced probability of aphids reaching EILs (Brewer and Elliott, 2004). Additionally, through crop rotations, these diverse systems can also allow for effective weed management and decreased disease levels (Blackshaw *et al.*, 1994, 2001; Wilson *et al.*, 1999; Boyles *et al.*, 2004). Results from the Kelsey and Mariger (2002) survey and the Keenan *et al.* (2007a, b) focus groups of wheat producers both clearly indicated that suppression of grassy weeds is the most important concern of producers in the Great Plains.

Crop diversification via intensive crop rotation also has agronomic and environmental benefits because, in many systems, rotational crops are increasingly grown no-till, leading to increased water use efficiency and reduced soil erosion (Peterson and Westfall, 1994, 2004; Peterson *et al.*, 1996). Long-term studies confirm that intensive rotations help to stabilize or increase farm net returns and reduce financial risk compared with monoculture wheat systems. For example, in Colorado annualized grain production from 1987 to 1993 in dryland wheat–maize–fallow and wheat–maize–millet–fallow was 72% higher than for wheat–fallow, with a 25–40% increase in net annual income (Dhuyvetter *et al.*, 1996). However, rotational options in the western Great Plains are driven by water availability: drier areas will have fewer rotational options, and this can greatly affect the income potential in these areas (Lyon *et al.*, 2004).

At the beginning of the project we anticipated that if cereal aphid AWPM was fully implemented, the direct economic benefits of reducing aphid densities in wheat would average US$75 million per year and that indirect benefits would exceed US$150 million, for a combined annual total of US$225 million. These figures were based on: (i) expected reductions in average aphid density across the Great Plains; (ii) documented relationships between aphid numbers and yield loss; (iii) reductions in costs associated with insecticide use in wheat systems; and (iv) reduced impact of other pests in farming systems. Benefits (~US$102 million) were also expected to result from increased profits from diversified crop rotations. For example, Boyles *et al.* (2004) suggest that rotations of winter canola with wheat result in 15% greater wheat grain yields compared with continuous systems. Difficult to estimate, but clearly important, are the additional long-term potential benefits of stabilizing farm economies and reduced soil erosion.

Designation of Demonstration Sites and Evaluation Methodology

During initial planning sessions, participants from each state (see Box 19.1) determined that programme evaluation would be conducted at three levels. First, economic data from surveys was collected from a broad pool of producers in each geographic zone (see Fig. 19.2 and below) using sample survey and focus group methodology. Secondly, a smaller pool of producers in each zone (three utilizing a diversified wheat production system and three farms using a monoculture wheat production system) were evaluated using an intensive survey of economic and agronomic variables. Thirdly, and the focus of this chapter, biological data were gathered from demonstration farms of each type in each zone to gather specific information on how pest and beneficial organism populations vary between cropping system type (monoculture versus diversified). The designation of paired demonstration sites throughout the region was a difficult challenge, but included ecological, environmental and farming system considerations.

Definition of study areas

The area of interest for the areawide IPM project, i.e. the portion of the Great Plains where GB and RWA are key pests of wheat (see Fig. 19.1), was divided into three geographic zones within which agroecological conditions are similar throughout. The following three zones were delineated (see Fig. 19.2):

- Northern zone (Zone 1): south-east Wyoming, Nebraska Panhandle, north-east Colorado; the RWA is the main pest of wheat in this zone. Possibilities for

Box 19.1. Principal investigators: biologically intensive AWPM of the Russian wheat aphid and greenbug.

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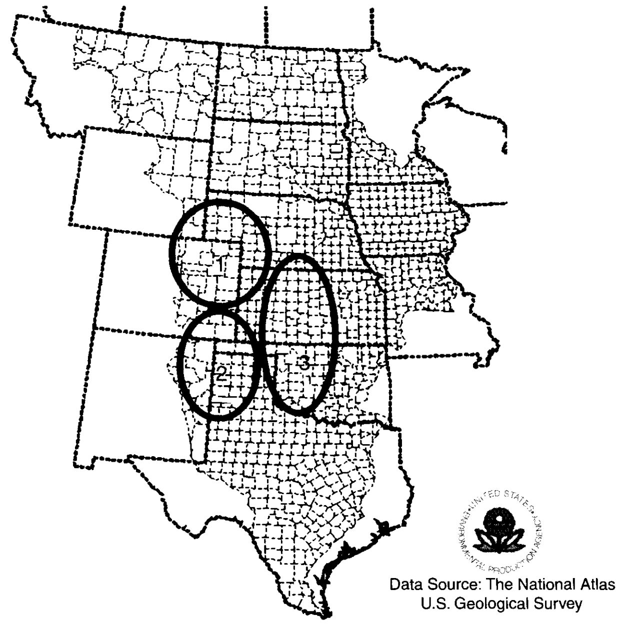

Fig 19.2. Geographic zones of the Cereal Aphid AWPM project.

rotational crops with wheat in this region are sunflower, maize, barley and proso millet.

- Southern zone (Zone 2): Texas Panhandle, Oklahoma Panhandle, south-east Colorado; RWA and GB are the main pests of wheat in this zone; sorghum is the only viable rotational crop to use with wheat.
- Eastern zone (Zone 3): central Oklahoma, central Kansas; GB is the main pest of wheat; soybean, sorghum, canola and cotton are the possibilities for rotational crops with wheat.

Selection of sites

With the assistance of county and regional extension professionals, we identified three paired farms for intensive evaluation per zone and, therefore, nine paired farm sites (18 farms) for the programme (see Fig. 19.3). Each pair consisted of one farm and surrounding areas, primarily defined by a monoculture wheat production system and one farm utilizing a diversified rotational wheat production system adapted to the area with resistant wheat cultivars if appropriate. The defined criteria for paired demonstration farms were:

- Each farm had at least 400 contiguous acres farmed, using identical cropping practices throughout.
- Each pair of farms were representative of farms specializing in a particular cropping system for the region, and were similar in terms of factors that determine agronomic and economic potential, such as soil type and topography.

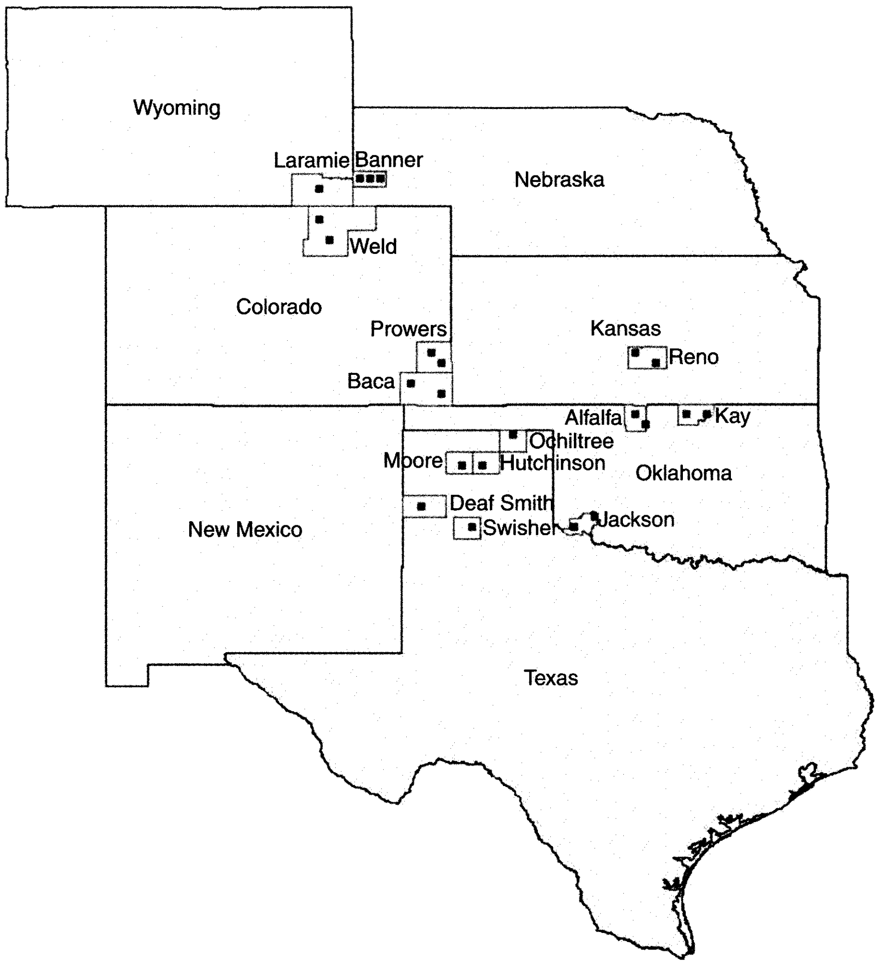

Fig. 19.3. Location of paired demonstration sites for the Cereal Aphid AWPM project.

- Within a particular zone, the rotational crop was standardized among farms. Therefore, farms with diversified farming that use the same alternative crop in rotation with wheat were chosen. One exception was made in Zone 3, where cotton is the most viable rotational crop in the southern portion.
- Farms and fields chosen for inclusion in the project must have had one cycle of the particular rotation completed prior to project initiation.

Insect and Weed Evaluation

Although a typical demonstration farm consisted of many fields, a single wheat field on a farm was deemed sufficient for the evaluation of insects and weeds. The minimum field size for sampling insects for research purposes was determined to be ¼ section (160 acres, 65 ha), with approximately one-half to one-third of the acreage in wheat in any year, depending on whether a monoculture or diversified crop rotation was being monitored. The 160-acre fields were divided into 25 uniformly sized 'quadrants' by using a 5 × 5 grid or other systematic division pattern. On each sampling date, samples were collected randomly near the centre of each quadrant. The pest species being sampled and data collection protocols for demonstration sites fields are outlined in Table 19.1.

Each location was monitored for 4 consecutive years, providing long-term data and information on pest abundance for monoculture (continuous or wheat–fallow) and diversified wheat systems. These data allow us to summarize long-term averages representative of each system and summarize the data by geographic zone.

In this chapter, data on aphid numbers, mummified aphids and visual counts of predators from wheat fields at each location were summarized by identified zone (Fig. 19.2). There are many ways to represent the data (i.e. peak numbers, field averages, seasonal accumulations); however, to account for all of the variability over a 4-year period, our focus will be on a comparison of averages per sample unit. The dynamics within and among growing seasons will be examined in future analyses.

Effectiveness of the Areawide Pest Management Programme at Controlling Target Pests

Over the 4-year period, annual sampling intensity varied among locations ranging from four to ten sampling events for individual fields (see Table 19.2). Low levels of

Table 19.1. Sampling methods for particular classes of pest and beneficial organisms.

Category sampled	Sampling method	Sampling frequency
Cereal aphids	25, 4–tiller counts (cut with scissors at ground level)[a]	Bi-weekly–monthly
	Berlese funnel (25 samples 0.15 m/field; samples included all soil and plant material from 0.1 m-wide shovel; samples left in funnels up to 1 week)[a]	
Cutworms and armyworms	Berlese funnel (25 samples 0.15 m/field)	Monthly
Wheat curl mite	Leaf samples	Seasonally
Natural enemies		
Predators	Sweepnet	Bi-weekly–monthly
	visual counts (25 samples 0.61 m/field)[a]	
Parasitoids	Mummies on stem counts	Bi-weekly–monthly
	Emergence canisters, trap plants[a]	Two times per year (trap plants)
Weeds	Area counts (25 samples 0.5 m^2/field)[a]	Once at appropriate time in each crop

[a] Data summarized for this chapter.

Table 19.2. Total samples for each sampling method, 2002–2006.

Sampling method	Zone	System	Sampling events (*n*)
4-stem counts (*n* = 25),	1	Diverse	54
visual counts and		Traditional	76
area weed counts	2	Diverse	101
		Traditional	112
	3	Diverse	70
		Traditional	77
Berlese funnel	1	Diverse	46
		Traditional	61
	2	Diverse	83
		Traditional	93
	3	Diverse	65
		Traditional	72

Table 19.3. RWA in each zone, 2002–2006.

Sampling method	Zone	System	RWA (%)
4-stem counts (*n* = 25)	1	Diverse	85
		Traditional	71
	2	Diverse	61
		Traditional	81
	3	Diverse	0
		Traditional	0
Berlese funnel	1	Diverse	92
(25 samples 0.1 m/field)		Traditional	94
	2	Diverse	52
		Traditional	65
	3	Diverse	0
		Traditional	0

aphids and natural enemies prompted reduced sampling efforts at several locations, whereas in fields with increasing pest levels, participants sampled more frequently to accurately reflect insect activity.

Cereal aphids in wheat

Cereal aphids were the most abundant pests found throughout the study. The relative proportion of RWA varied according to geographic zone; RWA constituted the majority of aphids identified in the more arid regions of the Great Plains (Zones 1 and 2, Fig. 19.1; Table 19.3). GB was the second most common aphid species found, followed by BCOA (*R. padi*), and relatively small numbers of rice root aphids (*Rhopalosiphum rufiabdominalis*), corn leaf aphids (*Rhopalosiphum maidis*) and English grain aphids (*Sitobion avenae*).

The data on aphid abundance (summed for all species) from demonstration plots for both the tiller and Berlese samples provide interesting trends relative to crop diversification and geographic zone. For each approach within a geographic zone, aphid numbers per sample unit were always greater (though not always significant) in wheat fields at 'monoculture' (continuous or wheat fallow) versus 'diverse' demonstration sites (see Figs 19.4 and 19.5).

Reduced aphid levels in the diverse sites in Zones 1 and 2 were also probably influenced by the use of aphid-resistant wheat. Very little difference was observed in Zone 3, where GB-resistant cultivars are not well adapted. The relative discrepancy in aphid numbers between tiller and Berlese sampling may reflect a lack of precision for estimating aphid intensity, especially RWA (Zone 1) with 100 tillers in a field and/or the absolute nature of the Berlese method. Either way, the trends indicate that diversified systems that incorporate aphid-resistant wheat have reduced

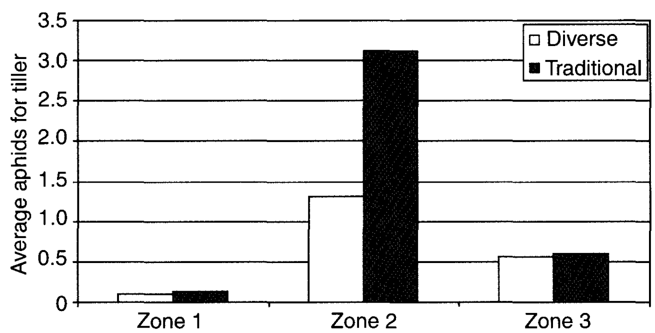

Fig. 19.4. Four-year (2002–2006) average number of aphids per tiller at AWPM demonstration sites.

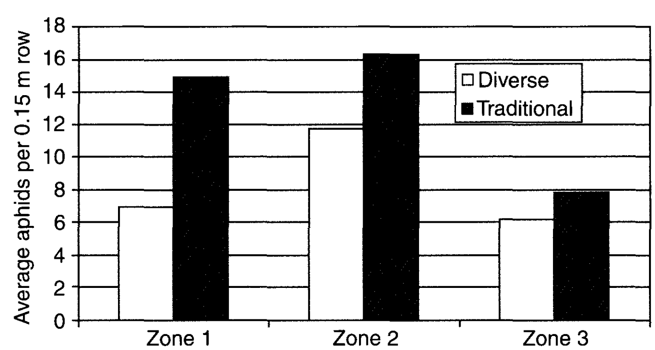

Fig. 19.5. Four-year (2002–2006) average number of aphids per 0.15 m at AWPM demonstration sites.

infestations of aphids. This appears to be especially true in zones where RWA is most prevalent.

Parasitoids and predators

The data presented on parasitism reflect the current summarization from field tiller sampling and are limited to counts of intact 'gold' and 'black' mummies. Preliminary identification and previous studies in the Great Plains (Gilstrap *et al.*, 1984; Giles *et al.*, 2003; Brewer and Elliott, 2004) suggest that these mummies are represented by *Lysiphlebus testaceipes* (gold mummies) and *Diaeretiella rapae* (black mummies). Data summarized over the 4-year period at demonstration sites indicate that the average number of mummies was quite low, and that no consistent trends were apparent between monoculture and diverse systems (see Fig. 19.6). Potentially, our resolution on measuring parasitism was inadequate, and/or parasitoid populations function at scales different from those evaluated in our study (Brewer and Elliott, 2004) or independent of production system diversity.

Comparing data on aphid abundance with mummy abundance may suggest that parasitoid impact can function independently of aphid densities; the highest average intensity for mummy counts was found in the wheat systems of Zones 2 and 3, where low aphid populations were found (see Figs 19.5 and 19.6). Of course, as suggested by Giles *et al.* (2003), during mild winters local populations of parasitoids in Oklahoma and Texas can function to maintain very low aphid levels; data from Zones 2 and 3 may reflect this cause and effect.

As expected, a common assemblage of predators (adult and immature) were observed in wheat fields throughout the study during visual sampling. These predators included species of Coccinellidae, Nabidae and other Hemipteran predators (species of *Geocoris* and *Orius*, etc.), predatory Carabidae, Staphlyinidae and spiders. Similar to mummies, data on total predators were low and no consistent trends were apparent between monoculture and diverse systems (see Fig. 19.7). The relatively high populations of predators at traditional sites within Zone 1 probably

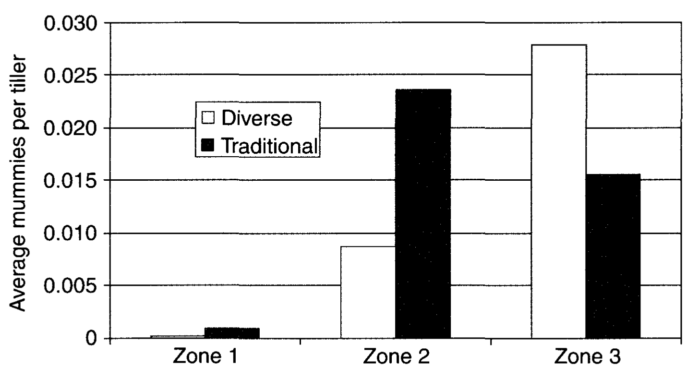

Fig. 19.6. Four-year (2002–2006) average number of mummies per tiller at AWPM demonstration sites.

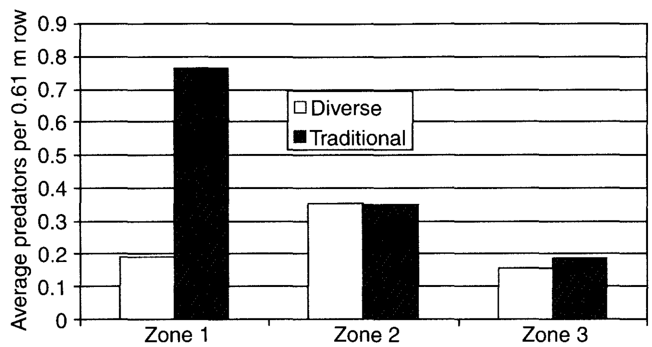

Fig. 19.7. Four-year (2002–2006) average number of all predators per 0.61 m of row at AWPM demonstration sites.

corresponded to the high counts of RWA found in Berlese samples (see Figs 19.5 and 19.7); for more aphidophagous predators such as Coccinellidae, which were often the most abundant group, we might expect this aggregative response to aphids. Hein (2006) demonstrated experimentally (cage exclusion) that this predatory response in Zone 1 was an essential component of RWA natural control; RWA numbers per 25 tillers were up to 40 times greater in cages that excluded natural enemies versus open-field plots.

Our data on predator numbers at demonstration sites do not support findings from studies that have documented increased abundance of predators in diversified systems (Brewer and Elliott, 2004). In fact, it appears as if predators primarily responded to aphid abundance. A careful evaluation of separate predator groups and their dynamics within and among fields is planned for the future.

Weeds

Grass weeds, including *Bromus* species, jointed goatgrass, wild oats and ryegrass, were very common; however, broadleaf weeds such as field bindweed, *Chenopodium*, pigweed and horseweed were prevalent in Zone 2 (see Fig. 19.8). Within a geographic zone, total weed densities were always higher in wheat fields at monoculture (continuous or wheat fallow) versus diverse demonstration sites (see Fig. 19.8). Based on focus group studies with producers in this AWPM programme (Keenan *et al.*, 2007a, b), lower weed densities at diversified sites were expected because producers are very concerned with long-term weed management. Most diversified farmers recommend rotation to a broadleaf crop and selective herbicide use as the only viable long-term strategy in wheat systems. For some time, weed scientists have documented lower weed densities in diversified rotational systems (Blackshaw *et al*, 1994, 2001; Lyon and Baltensperger, 1995; Boyles *et al.*, 2004), and our results provide additional supportive data for producers who are addressing weed problems through crop rotation.

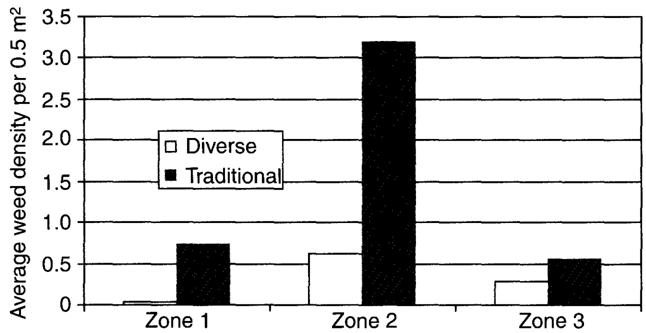

Fig. 19.8. Four-year (2002–2006) average weed densities per 0.5 m^2 at AWPM demonstration sites.

Unintended Consequences of the Areawide Pest Management Programme

During the project (2001–2006), some major developments occurred that were not necessarily planned. We had planned that all participants in the project would document and quickly communicate any new findings; however, we did not anticipate the rapid build-up of RWA-biotype 2 (Peairs, 2006), which can overcome available RWA-resistant cultivars and is currently the dominant biotype in Colorado and surrounding states. Producers in Zone 1 were made aware of this development, and some participated in documenting the regional prevalence of RWA-2. The focus groups and interviews established an instant and now long-term network of producers who continue to interact directly with AWPM personnel. We believe this group of producers will continue to work with state personnel, providing farming system results and stakeholder recommendations that will drive future research and extension programmes.

This AWPM programme also allowed for delivery of new IPM tools. The '*Glance n' Go*' greenbug + parasitism sampling and management plan was fully developed during this project, and communicated project-wide and throughout the Great Plains as the recommended approach for GB sampling and decision making (Giles *et al.*, 2003; Elliott *et al.*, 2004; Royer *et al.*, 2004a, b, 2007). Participating producers demonstrated the usefulness of this approach on many of their farms.

The project was conducted during a period of severe drought throughout much of the Great Plains. The results of the project during these years demonstrated the impact of drought on monoculture and diversified wheat-cropping systems. In the more arid areas of the project, the benefits of diversity were reduced and the benefits of the monoculture cropping system were enhanced. These differences resulted from the moisture-saving advantages seen in the wheat–fallow (monoculture) systems.

Summary and Future Directions

Relative to AWPM for GB and RWA, lack of information on the dispersal range and extent of migration for aphids and natural enemies hinders the full development of an optimal AWPM strategy (Booij and Noorlander, 1992; Brewer and Elliott, 2004; Vialatte *et al.*, 2006). Based on our methodology for demonstration sites, we could not determine the spatial extent of the suppression area required to minimize colonization of aphids and conserve natural enemies. Further analysis and modelling evaluation of within-season dynamics may help to define regional trends that could be useful in defining appropriate spatial scales for areawide implementation. The sporadic nature of GB and RWA infestations in wheat is also an impediment to the development of areawide programmes focused on aphid management. Producers of this low-value crop are increasingly willing to use low-input strategies such as resistant cultivars (Peairs, 2006) to manage aphids; however, many are reluctant to significantly alter production practices to avoid pests that are not a problem annually (Keenan *et al.*, 2007a, b).

There are four important reasons why we believe that producers will move towards diversification of wheat systems in the Great Plains. First, studies continue to support the idea that diversification of farming systems increases water use efficiency and stabilizes and/or increases farm profits (Peterson and Westfall, 1994, 2004; Dhuyvetter *et al.*, 1996; P. Burgener and S. Keenan, unpublished data). Secondly, fuel and equipment costs related to tillage continue to increase, prompting a shift by producers towards no-till rotational production systems. Thirdly, wheat producers in this region continue to consider weed problems as their most serious pest problem and are becoming increasingly aware of how diversified farming systems allow for more effective long-term selective weed management. Finally, cropping system diversification provides numerous benefits for the management of several other pests. As growers strive to become more cost-efficient, many of these benefits will become more apparent when compared with the alternative of relying on increasingly more costly pesticides.

This anticipated diversification of wheat-farming systems in the Great Plains will probably provide opportunities for evaluation of AWPM of cereal aphids on increasingly larger spatial scales. Findings from this future work may help producers and scientists in designing the most effective areawide approach for each region of the Great Plains.

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