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Herbicide-Resistant Grass Weed Development in Imidazolinone-Resistant Wheat: Weed Biology and Herbicide Rotation[1]

CURTIS R. RAINBOLT, DONALD C. THILL, JOSEPH P. YENISH, and DANIEL A. BALL[2]

Abstract: A general life cycle model was modified to demonstrate how agronomic practices and weed biology factors affect the rate of appearance of herbicide-resistant downy brome, jointed goatgrass, and wild oat in Pacific Northwest wheat cropping systems. The model suggests herbicide rotation strategies for cropping systems that include imidazolinone-resistant wheat as a weed management tool. Simulation of continuous annual imidazolinone-resistant winter wheat and imazamox herbicide use resulted in the resistant soil seed banks of downy brome, jointed goatgrass, and wild oat surpassing their susceptible soil seed banks in 5, 7, and 10 yr, respectively. Reducing the initial seed bank density of downy brome before beginning a rotation that includes imidazolinone-resistant winter wheat reduces the likelihood of selecting for herbicide-resistant biotypes. The best simulated management option for reducing the total jointed goatgrass soil seed bank in low-precipitation areas is an imidazolinone-resistant winter wheat–fallow rotation. Rotations that include winter and spring crops and rotations that include non–group 2 herbicides minimize herbicide resistance selection pressure and reduce the wild oat soil seed bank.

Nomenclature: Imazamox; downy brome, *Bromus tectorum* L. # BROTE; jointed goatgrass, *Aegilops cylindrica* Host #3 AEGCY; wild oat, *Avena fatua* L. # AVEFA; winter wheat, *Triticum aestivum* L. Clearfield™.

Additional index words: Crop rotation, population model, resistance management.

Abbreviations: ALS, acetolactate synthase; PNW, Pacific Northwest.

INTRODUCTION

Imidazolinone-resistant (Clearfield™) winter wheat is available currently to Pacific Northwest (PNW) wheat producers. Imazamox, an acetolactate synthase (ALS)–inhibiting herbicide, applied to imidazolinone-resistant winter wheat selectively controls jointed goatgrass, downy brome, wild oat, and other grass weeds (Ball et al. 1999; Dahmer et al. 2002). However, many ALS-inhibiting herbicides (group 2; sulfonylureas, imidazolinones, sulfonylaminocarbonyl-triazolinones, and others) are used extensively in wheat-based cropping systems because they affordably and effectively control many important weed species. Imazamox applied to imidazolinone-resistant winter wheat will increase group-2 herbicide use for grass weed control, especially in crop rotations where winter wheat is grown frequently. Frequent use of this technology may result in the selection of herbicide-resistant weed populations in a relatively short time period as has occurred previously for several group 2 herbicides used extensively for broadleaf weed control (Mallory-Smith et al. 1990).

Numerous agronomic and biological factors affect the selection and development of herbicide-resistant weed populations (Jasieniuk et al. 1996). Important agronomic factors include herbicide-use patterns, crop rotations, level of control achieved with herbicides, and tillage practices. Biological factors that influence resistance development include initial weed densities, longevity of seed in the seed soil bank, seed produced, the number of seed that germinate each year, the number of seed that are dormant, and the initial frequency of resistance (Cavan et al. 2001; Hanson et al. 2002).

Group 2 herbicides, such as imazamox, are more prone to select for resistant weed populations than other herbicide groups because plants can have several naturally occurring isoforms of the ALS enzyme (Saari et al. 1994). The actual frequency of mutations for herbicide resistance is unknown for most weeds, but the natural, spontaneous mutation rate for a single gene is estimated to be between 1:100,000 and 1:1,000,000 per generation

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[2] Former Graduate Research Associate and Professor, respectively, Department of Plant, Soil, and Entomological Sciences, University of Idaho, Moscow, ID 83844-2339; Associate Professor, Department of Crop and Soil Sciences, Washington State University, Pullman, WA 99164-6416; Professor, Columbia Basin Agricultural Research Station, Oregon State University, Pendleton, OR 97801. Corresponding author's E-mail: crrainbolt@ifas.ufl.edu.

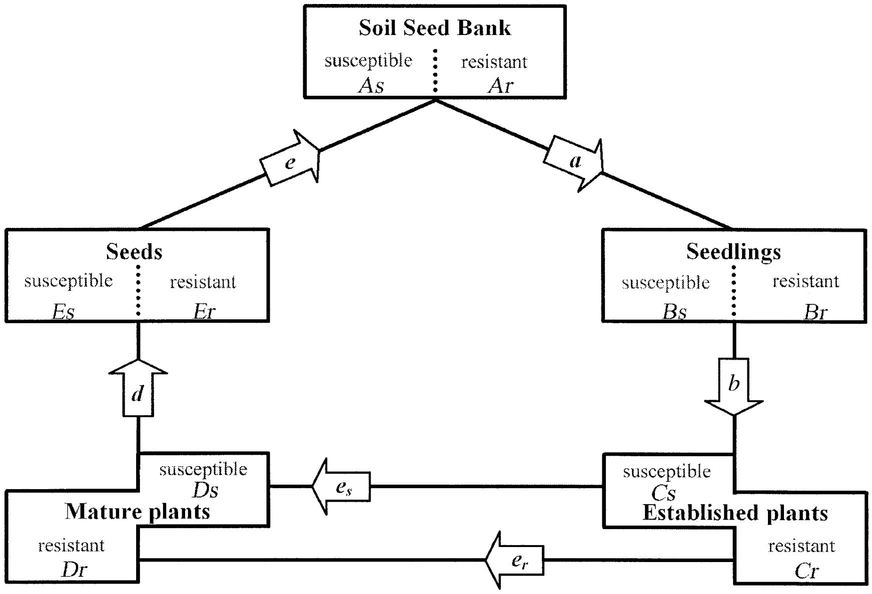

Figure 1. Life table model for population change of susceptible (*s*) and herbicide-resistant (*r*) weed biotypes. Uppercase italics (*X*) indicate life cycle stages; lowercase italics (*x*) indicate transition rates. Stages are labeled and transition rates are (*a*) germination, (*b*) natural seedling mortality, (c_s) herbicide induced mortality rate for susceptible biotypes, and (c_r) herbicide induced mortality rate for resistant biotypes, (*d*) seed production (seeds/plant), and (*e*) seed loss (predation, removal at harvest, decay). Seed immigration is not included in the model.

(Mortimer et al. 1992). Given a weed seed density for a single species of 1,000,000 seeds/0.405 ha, there is a probability that at least one seed could contain the mutation for herbicide resistance. Most research estimates the number of weed seeds in agricultural soils to be between 13,000,000 and 435,000,000 seeds/0.405 ha (a total for multiple weed species) (Wilson 1988). On the basis of these numbers, it can be assumed that small populations of ALS-resistant weeds are already present in some fields, even if they have never been sprayed with group 2 herbicides. In most cases, herbicide-resistant populations go undetected until they represent about 30% of the total population because weed control is rarely 100% (Mallory-Smith et al. 1999).

A model was developed to demonstrate how certain agronomic practices and weed biology factors affect the rate of appearance of herbicide-resistant weeds. Modeling is commonly used to study the development of herbicide-resistant weed populations because it provides a timely method, compared with field experimentation, of evaluating the long-term influence of many factors and comparing management strategies (Hanson et al. 2002). The model is a general life cycle table for annual weed species modified to account for the development of herbicide-resistant biotypes (Figure 1). The model was designed to determine the influence of herbicide and crop rotation, seed germination, seedling mortality, herbicide-induced mortality or control, seed production, seed loss (predation, removal at harvest, and decay), initial seed bank density, and the naturally occurring frequency of group 2 herbicide resistance on the ratio of susceptible to resistant weed seeds in the soil seed bank with time.

The objective of this project was to develop a model that could be used as an extension teaching tool to demonstrate the effect of weed biology and crop rotation on the development of herbicide-resistant populations and to provide PNW growers a simple tool for developing herbicide rotation strategies for PNW dryland cropping systems that use imidazolinone-resistant wheat as a weed management tool.

MATERIALS AND METHODS

Fifteen different scenarios (Table 1) were modeled to simulate three different grass weed problems in several major winter wheat cropping systems found across the precipitation zones of the inland PNW. Jointed goatgrass can be problematic for producers in all cropping regions and crop rotations. Downy brome tends to be more troublesome in low-precipitation winter wheat–fallow and intermediate-precipitation winter wheat–spring wheat rotations; however, it can be a problem in high-precipitation zones if diverse crop rotations are not used. Wild oat occurs mostly in intermediate- and high-precipitation cropping systems. These three species were chosen because they are economically important and differ in their biological characteristics.

When possible, model parameters were based on pub-

Table 1. Cropping system and weed species scenarios used in the herbicide-resistant weed-prediction model for imidazolinone-resistant winter wheat production in the inland Pacific Northwest.

Weed species/rotation[a]	Precipitation zone[b]
Downy brome	
Continuous annual IR wheat	
IR wheat–fallow	Low
IR wheat–fallow–winter wheat–fallow	Low
IR wheat–spring wheat	Intermediate
IR wheat–spring wheat–winter wheat–spring wheat	Intermediate
Jointed goatgrass	
Continuous annual IR wheat	
IR wheat–fallow	Low
IR wheat–fallow–winter wheat–fallow	Low
IR wheat–spring wheat	High/intermediate
IR wheat–spring wheat–spring pea	High
IR wheat–spring wheat–spring pea–winter wheat–spring wheat–spring pea	High
Wild oat	
Continuous annual IR wheat	
IR wheat–spring wheat	High/intermediate
IR wheat–spring wheat–spring pea	High
IR wheat–spring wheat–spring pea–winter wheat–spring wheat–spring pea	High

[a] IR wheat denotes imidazolinone-resistant winter wheat.

[b] Precipitation zones: low is less than 30 cm, intermediate is 31–49 cm, and high is greater than 50 cm of annual precipitation (Roger Veseth, personal communication).

lished research; otherwise, estimates from local experts were used. When multiple different values were found in the literature, the more conservative data or estimates were used. However, it is important to note that in some field situations the initial seed bank density, natural frequency of herbicide resistance (mutation rate), and other factors may be considerably higher resulting in faster selection of herbicide-resistant weed populations.

Resistance to ALS-inhibiting herbicides, such as imazamox, is inherited as a semidominant trait (Saari et al. 1994). Our model (Figure 1) used a frequency of 1: 1,000,000 for mutations conferring ALS resistance (Mortimer et al. 1992). Seed dormancy, seed loss, plant fitness, and agronomic practices were considered equal and held constant for both resistant and susceptible biotypes (Alcocer-Ruthling et al. 1992; Thompson and Thill 1994); therefore all parameters were the same except for resistance or susceptibility to ALS-inhibiting herbicides. For simplicity, the initial soil seed bank density for all simulations was set at 1,000,000 seeds/0.405 ha, which is equal to one resistant and 999,999 susceptible seeds/ 0.405 ha. Natural seedling mortality (not caused by the herbicide) was calculated as a function of weed seedling density with the following equation

$$M = \ln (D^4 + 1)0.01, \qquad [1]$$

where M is natural seedling mortality and D is weed seedling density (seedlings/0.405 ha). The equation is an exponentially increasing curve, where seedling mortality increases as weed seedling density increases. Weed seed production also was calculated as a function of weed seedling density using the following equation

$$S = P(1 - (0.1 \times \log (D + 0.01)), \qquad [2]$$

where S is seed production (seeds/plant), P is seed production of a single plant in the absence of competition, and D is weed seedling density (seedlings/0.405 ha). The equation is an exponentially decreasing curve, where weed seed production per plant decreases as seedling density increases. Weed seed loss (Figure 1), which consists of seed predation, removal at harvest, and decay was estimated to be 70% annually for all simulations (Cavan et al. 2001). Annual weed seed germination rates and annual seed production per plant (Figure 1) were 30% and 50 seeds/plant for wild oat, respectively (Chancellor and Peters 1972; Quail and Carter 1968). For jointed goatgrass, the seed germination rate was 50% and seed production was 75 seeds/plant (Anderson et al. 2002; Donald and Ogg 1991; Gealy 1988). The germination rate was 85% and seed production was 150 seeds/ plant for downy brome (Evans and Young 1972; Laude 1956; Thill et al. 1980). Herbicide induced mortality (control) (Figure 1) of susceptible biotypes with imazamox was estimated to be 95% for jointed goatgrass and wild oat and 98% for downy brome, whereas resistant biotypes were not susceptible and control was 0% (Ball and Walenta 1997; Ball et al. 1999; Belles and Thill 1998). In fallow simulations, control was assumed to be

100% with tillage, burndown herbicides, or a combination of both (Hanson et al. 2002). Wild oat control was 95% in spring wheat and 99% in spring peas in years where an alternate crop and an alternate herbicide mode of action were used. Jointed goatgrass is typically not a problem in spring crops (Young et al. 2003), and control was estimated to be 98% in spring wheat and spring pea. Downy brome control in spring wheat was estimated to be 98%. In standard winter wheat (nonimidazolinone resistant), control with non–group 2 herbicides was 95% for wild oat and 75% for downy brome. Jointed goatgrass was not controlled in a standard winter wheat crop.

RESULTS AND DISCUSSION

The model was designed to demonstrate the influence of weed biology and crop rotation on the evolution of herbicide-resistant weed populations on a relative time frame; however, the ability of the model to accurately predict how fast a resistant population may grow is limited. The addition of more complex and realistic population-limiting parameters to account for spatial and temporal differences in germination, dormancy, seedling mortality, and seed production would improve the predictive ability of the model.

Downy Brome Simulations. Simulation of continuous annual imidazolinone-resistant winter wheat and imazamox use resulted in the resistant downy brome soil seed bank surpassing the susceptible soil seed bank in 5 yr, followed by very rapid increase of the resistant and total soil seed bank (Figure 2A). By year 6, the number of downy brome seeds in the soil seed bank exceeded the initial population.

Low-precipitation zone rotations. The imidazolinone-resistant winter wheat–fallow simulation resulted in the resistant soil seed bank surpassing the susceptible soil seed bank in 8 yr, and in year 9, the total soil seed bank was about 500 seeds/0.405 ha or 0.05% of the initial soil seed bank population (Figure 2B). By year 15, the total number of seeds in the soil was reduced to about 15,000 seeds/0.405 ha or 98.5% compared with the initial population. In the imidazolinone-resistant winter wheat–fallow–standard winter wheat–fallow simulation, the total soil seed bank was 2,000 seeds/0.405 ha or 99.8% less than the initial total soil seed bank in year 9 and 300 seeds/0.405 ha or 99.97% less in year 11 (Figure 2C). In year 13, the resistant soil seed bank surpassed the susceptible soil seed bank, resulting in growth of the total soil seed bank in subsequent years.

Intermediate-precipitation zone rotations. In the imidazolinone-resistant winter wheat–spring wheat simulation (Figure 2D), the resistant soil seed bank surpassed the susceptible soil seed bank in 7 yr compared with 10 yr in the imidazolinone-resistant winter wheat–spring wheat–standard winter wheat–spring wheat simulation (Figure 2E). By year 7 of the imidazolinone-resistant winter wheat–spring wheat simulation, the total soil seed bank was approximately 20,000 seeds/0.405 ha or 98% less than the initial soil seed bank but exceeded 1,000,000 seeds/0.405 ha by year 12. The total soil seed bank in the imidazolinone-resistant winter wheat–spring wheat–standard winter wheat–spring wheat simulation was 40,000 seeds/0.405 ha or 96% less than the initial total soil seed bank in year 7 but exceeded 1,000,000 seeds/0.405 ha by year 14 because both the susceptible and resistant populations increased during nonimidazolinone-resistant winter wheat years. The higher level of control achieved in fallow (100%) compared with spring wheat production (98%) increased the resistant soil seed bank faster in the intermediate-precipitation simulations than in the low-precipitation simulations.

Management. The ability of downy brome to produce many germinable seeds results in a large number of subsequent seedlings being exposed to the herbicide selection pressure, which greatly increases the likelihood of selecting for group 2 herbicide–resistant biotypes. Consequently, annual use of imidazolinone-resistant winter wheat treated with imazamox or other group 2 herbicides for control of downy brome is a poor weed management strategy.

In low-precipitation zone fields with serious downy brome infestations, it may be advisable to initially use imidazolinone-resistant winter wheat or other group 2 herbicides for 2 of 4 yr and reduce the population to a manageable level (5,100 seeds/0.405 ha after the second fallow period if 1,000,000 seeds were present initially). Once the population is reduced, a rotation that uses imidazolinone-resistant winter wheat less frequently can keep the population in check while minimizing selection of resistant plants. To test this management scheme, a simulation of imidazolinone-resistant winter wheat–fallow–imidazolinone-resistant winter wheat–fallow–standard winter wheat–fallow (6 yr) followed by an ongoing rotation of imidazolinone-resistant winter wheat–fallow–standard winter wheat–fallow for 9 yr was conducted. After the first 6 yr, the soil seed bank was reduced to 4,000 seeds/0.405 ha or 99.6% less than the initial soil seed bank and less than 1% of the remaining seeds were resistant. In year 15, the total soil seed bank was only

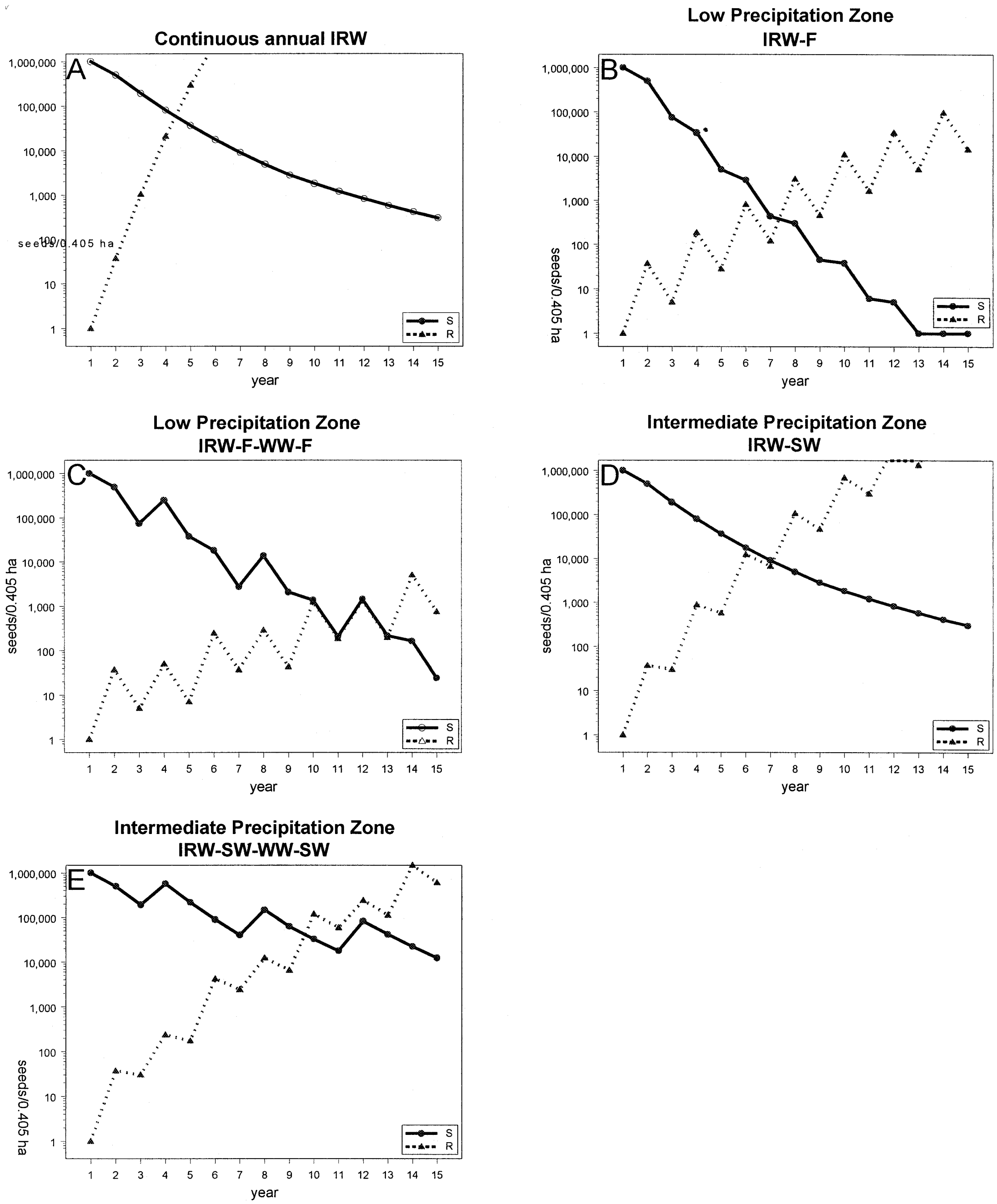

Figure 2. Downy brome simulations: (A) continuous annual imidazolinone-resistant winter wheat (IRW); (B) IRW and fallow (F); (C) IRW, F, standard winter wheat (WW), and F; (D) IRW and spring wheat (SW); and (E) IRW, SW, WW, and SW.

500 seeds/0.405 ha or 99.95% less than the initial total. In fields with dense populations of downy brome, there are more seeds and consequently a greater chance of selecting for resistant biotypes. It is a responsible management practice in these situations to initially use imidazolinone-resistant winter wheat more frequently to reduce the population, perhaps 2 or 3 yr out of the first 6 yr. This does increase selection pressure, but also quickly reduces the population, which may be an acceptable compromise.

Downy brome can become a major problem in any rotation that includes frequent winter crops. Growing consecutive spring crops in intermediate-precipitation zone rotations can greatly reduce the number of downy brome seeds in the soil seed bank. Reducing the initial seed bank density of downy brome before beginning a

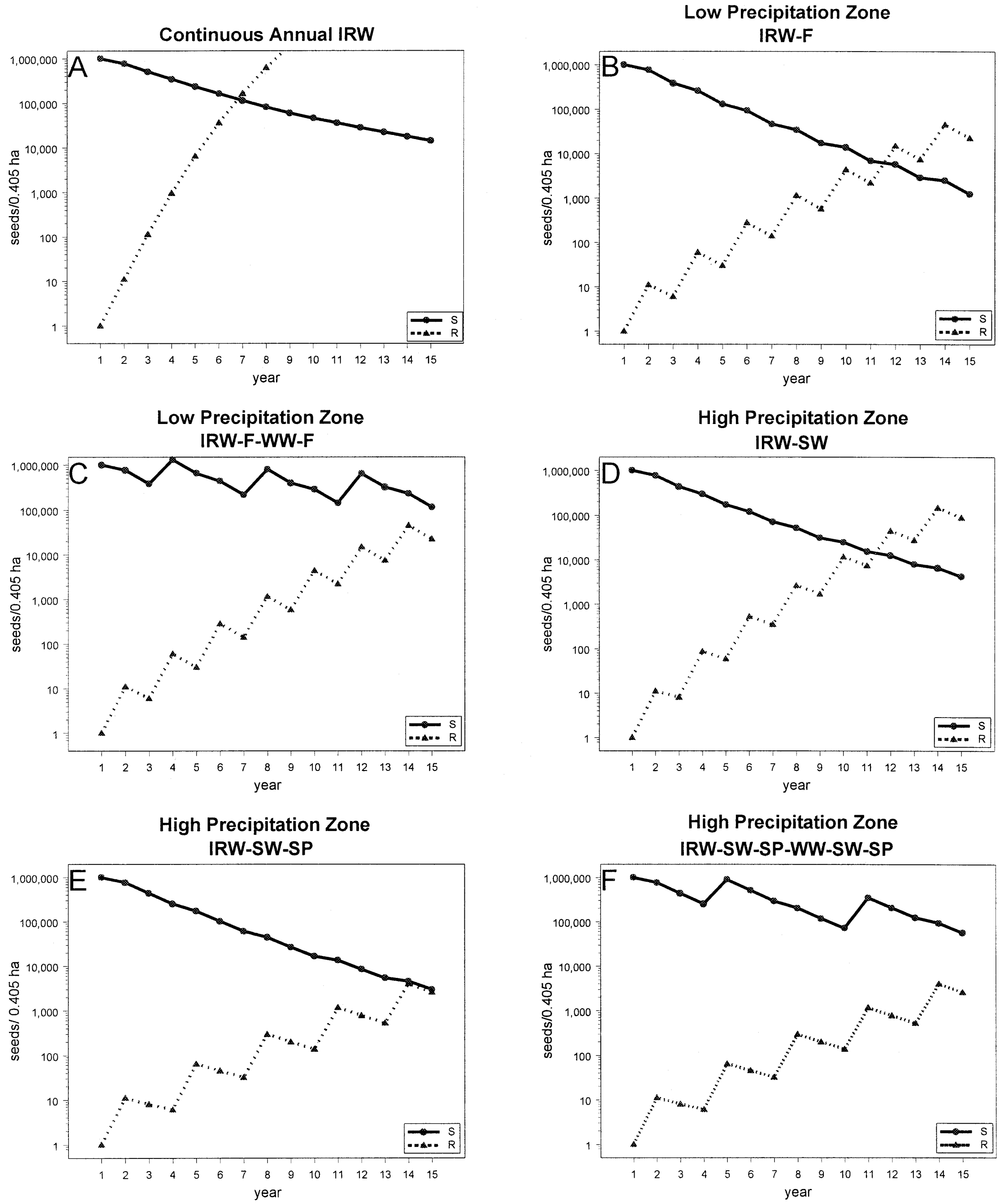

Figure 3. Jointed goatgrass simulations: (A) continuous annual imidazolinone-resistant winter wheat (IRW); (B) IRW and fallow (F); (C) IRW, F, standard winter wheat (WW), and F; (D) IRW and spring wheat (SW); (E) IRW, SW, spring pea (SP); and (F) IRW, SW, SP, WW, SW, and SP.

rotation that includes imidazolinone-resistant winter wheat can reduce the likelihood of selecting for herbicide-resistant biotypes. A simulation of two consecutive spring crops reduced the initial susceptible soil seed bank to approximately 190,000 seeds/0.405 ha or 19% of the initial density. In year 15, the resistant soil seed bank in a simulation of two spring crop years followed by an imidazolinone-resistant winter wheat–spring wheat–standard winter wheat–spring wheat rotation was about 10 times less than in the imidazolinone-resistant winter wheat–spring wheat–standard winter wheat–spring wheat simulation.

Jointed Goatgrass Simulations. Continuous annual use of imidazolinone-resistant winter wheat and imazamox resulted in the resistant jointed goatgrass soil seed bank surpassing the susceptible soil seed bank in year 7 (Figure 3A). The total soil seed bank in this simulation was

80% less than the initial total soil seed bank in year 6 but by year 9 was more than double the initial total soil seed bank.

Low-precipitation zone rotations. In year 11 of the imidazolinone-resistant winter wheat–fallow simulation, the total soil seed bank was about 10,000 seeds/0.405 ha or 99% less than the initial seed bank. However, by year 12, the resistant soil seed bank surpassed the susceptible soil seed bank (Figure 3B). In the imidazolinone-resistant winter wheat–fallow–standard winter wheat–fallow simulation (Figure 3C), the resistant soil seed bank never exceeded the susceptible soil seed bank. However, the resistant soil seed bank density was the same for the imidazolinone-resistant winter wheat–fallow and the imidazolinone-resistant winter wheat–fallow–standard winter wheat–fallow simulations. The susceptible soil seed bank for the imidazolinone-resistant winter wheat–fallow–standard winter wheat–fallow rotation declined slowly because seed number increased almost fourfold after standard winter wheat crops because of a lack of jointed goatgrass control. The total soil seed bank for the imidazolinone-resistant winter wheat–fallow–standard winter wheat–fallow rotation was 140,000 seeds/0.405 ha or 86% less than the initial total soil seed bank in year 15. After year 11 of the imidazolinone-resistant winter wheat–fallow rotation, the total soil seed bank continued to grow because the resistant soil seed bank continued to increase with time.

High-precipitation zone rotations. In the imidazolinone-resistant winter wheat–spring cereal rotation, the resistant soil seed bank surpassed the susceptible soil seed bank in year 12 (Figure 3D), which is similar to the imidazolinone-resistant winter wheat–fallow simulation. However, the total number of seeds in the soil in the high-precipitation zone simulation was almost fourfold higher because jointed goatgrass control in spring wheat was estimated to be 98% compared with 100% during fallow. The total soil seed bank in the imidazolinone-resistant winter wheat–spring wheat rotation was 20,000 seeds/0.405 ha or 98% less compared with the initial total soil seed bank population in year 11 but increased in subsequent years as the number of resistant seeds in the soil seed bank increased. The resistant soil seed bank did not exceed the susceptible soil seed bank in the imidazolinone-resistant winter wheat–spring wheat–spring pea rotation (Figure 3E) or in the imidazolinone-resistant winter wheat–spring wheat–spring pea–standard winter wheat–spring wheat–spring pea rotation (Figure 3F). The jointed goatgrass seed population was 5,000 seeds/0.405 ha or 99.5% less by year 15 of the imidazolinone-resistant winter wheat–spring wheat–spring pea simulation. The total soil seed bank in year 15 of the imidazolinone-resistant winter wheat–spring wheat–spring pea–standard wheat–spring wheat–spring pea rotation was 60,000 seeds/0.405 ha or 94% less than the initial total soil seed bank.

Management. Continuously growing imidazolinone-resistant winter wheat or standard winter wheat (no herbicide is available for control) is a poor strategy for reducing severe jointed goatgrass infestations. Jointed goatgrass is a winter annual and germinates primarily in the fall. Consequently, jointed goatgrass tends to be a larger problem in 2-yr winter wheat–spring crop rotations than in rotations that include 2 or more years of spring crops. The lack of a herbicide for selective control of jointed goatgrass in wheat is a major factor contributing to the severity of jointed goatgrass infestations in winter wheat.

Winter wheat–fallow is currently the most economically feasible rotation in lower precipitation zones and consequently, jointed goatgrass control options are limited (Young et al. 2000). On the basis of model simulations, the best management option for reducing the total soil seed bank in low-precipitation areas is an imidazolinone-resistant winter wheat–fallow rotation. Although this rotation imposes high selection pressure, it is the only effective rotation for reducing jointed goatgrass infestations. Once a group 2 herbicide resistant jointed goatgrass plant is selected, it likely will remain in the population because there are no other herbicides for jointed goatgrass control in standard winter wheat crops. Thus, control in fallow is critical because it is the only opportunity to control resistant biotypes. However, the intermediate-dormancy level of jointed goatgrass allows seeds produced in a single year to survive and germinate during a period of 1 to 5 or more years. Other practices for reducing jointed goatgrass include growing spring crops or winter canola or rapeseed or mustard crops that can be sprayed with group 1 herbicides.

Spring crops, particularly when combined with later seeding dates, are an effective means to control jointed goatgrass in higher precipitation zones (Young et al. 2003). A model simulation of two consecutive spring crops reduced jointed goatgrass populations to approximately 350,000 seeds/0.405 ha (65% less than the initial). The chance of selecting a resistant biotype is less if the jointed goatgrass population is reduced before using imidazolinone-resistant winter wheat. Susceptible and group 2–resistant jointed goatgrass plants cannot be

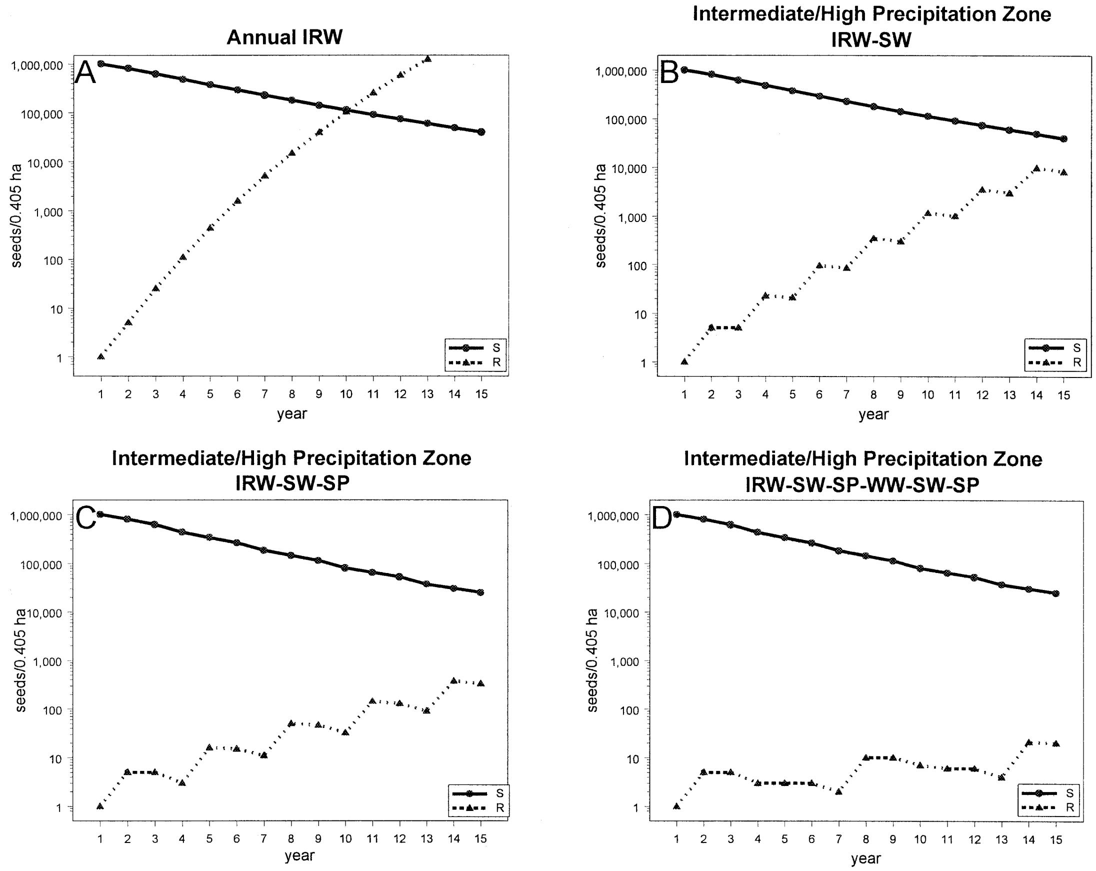

Figure 4. Wild oat simulations: (A) continuous annual imidazolinone-resistant winter wheat (IRW); (B) IRW and spring wheat (SW); (C) IRW, SW, spring pea (SP); and (D) IRW, SW, SP, standard winter wheat (WW), SW, and SP.

controlled in standard winter wheat crops until a new herbicide (non–group 2) is available to selectively control jointed goatgrass in winter wheat. Consequently, a group 2–resistant jointed goatgrass biotype can only be controlled with tillage, spring crops, or group 1 herbicides applied to winter-sown broadleaf crops.

Wild Oat Simulations. Continuous annual use of imidazolinone-resistant wheat and imazamox herbicide resulted in the resistant soil seed bank surpassing the susceptible soil seed bank in year 10, and by year 15 the total soil seed bank was 9.3 times larger than the initial total soil seed bank (Figure 4A).

Intermediate- and high-precipitation zone rotations. The resistant soil seed bank never surpassed the susceptible soil seed bank in simulations of imidazolinone-resistant winter wheat in rotation with spring wheat (Figure 4B), spring wheat and spring pea (Figure 4C), or spring wheat, spring peas, and standard winter wheat (Figure 4D). By year 15, the total soil seed bank was approximately 50,000 seeds/0.405 ha or 95% less than the initial soil seed bank for the imidazolinone-resistant winter wheat–spring wheat simulation. However, about 17% (8,500 seeds/0.405 ha) of the remaining total soil seed bank was herbicide resistant. The imidazolinone-resistant winter wheat–spring wheat–spring pea and the imidazolinone-resistant winter wheat–spring wheat–spring pea–standard winter wheat–spring wheat–spring pea simulation both had a susceptible soil seed bank of about 25,000 seeds/0.405 ha (97.5% less than the original soil seed bank) in year 15, but the resistant soil seed bank was only 20 seeds/0.405 ha in the 6 yr rotation compared with 331 seeds/0.405 ha in the 3-yr rotation.

Management. Low seed production and high seed dormancy are the primary reasons why the resistant soil seed bank of wild oat increased more slowly than the resistant soil seed bank of downy brome or jointed goatgrass. They also cause the susceptible soil seed bank to decline slowly. In species with low seed dormancy, most seeds produced in a single year germinate and seedlings are exposed to the herbicide. Resistant biotypes are quickly selected when herbicides with the same mode of action are applied annually. High seed dormancy results in germination of only a portion of the seed produced in a single year, which results in less selection pressure. The availability of graminicides (group 1) and difenzoquat (group 8) for wild oat control during standard winter wheat and spring crop years makes longer, more diverse rotations a good management choice. However, wild oat biotypes resistant to group 1, -2, and -8 herbicides have been reported where these herbicides have been used frequently. The ability of wild oat to establish in both fall- and spring-seeded crops makes it a problem in most years of a cropping system. The best rotation to minimize selection pressure and reduce the total wild oat soil seed bank includes both winter and spring crops and careful rotation of group 1, -2, and -8 herbicides. Use of glufosinate-resistant canola or glyphosate-resistant canola crops in a crop rotation would diversify herbicide usage and reduce the potential of selecting an herbicide-resistant wild oat biotype.

The imidazolinone-resistant winter wheat production system will be a valuable weed management tool for the inland PNW. However, excessive use of this technology or other group 2 herbicides (or both) may lead to rapid selection of herbicide-resistant weed biotypes. Judicious use of group 2 herbicides is key to preventing the selection of ALS-resistant weed populations. There are no other herbicides available to control jointed goatgrass in winter wheat, which makes resistance management more difficult. Where environmentally and economically possible, jointed goatgrass management strategies should include spring crops, winter broadleaf crops, or fallow years. Use of rotations that do not include a standard winter wheat crop until weed populations are reduced to manageable levels may be necessary in fields with severe jointed goatgrass and downy brome infestations. Long-term rotations that include standard winter wheat crops and spring crops not treated with group 2 herbicides will effectively control wild oat, and avoid selecting for group 2–resistant weed populations.

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