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Integrated Strategies for Management of Perennial Weeds

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Multiple weed control strategies employed in combination can often aid the successful management of perennial weed species. This review article provides examples of integrated control programs that could aid in the management of several invasive perennial weed species that are problematic in the Pacific Northwest and elsewhere in North America. The development of an integrated management control program for wild chervil, a relatively recent invader to the Pacific Northwest of the United States and adjacent Canada, provides an example for this process. Through use of mechanical (mowing and tillage), cultural (establishment of competitive vegetation), and chemical (specific herbicides) strategies, control of this short-lived perennial species was greatly improved as compared to foliar herbicide applications alone. Such integrated strategies have been shown to enhance control of many perennial weed species, while potentially reducing the amount of herbicide applied, lessening the possibility of injury to adjacent desirable vegetation and increasing the stability of the ecological community at the site.

Nomenclature: Aminocyclopyrachlor; aminopyralid; clopyralid; dicamba; fluazifop; fluroxypyr; glyphosate; imazapic; imazapyr; imazethapyr; mecoprop; picloram; triclopyr; 2,4-D; wild chervil, *Anthriscus sylvestris* (L.) Hoffmann.

Key words: Biocontrol of weeds, cultural weed control, herbicides, invasive species, mechanical weed control, noxious weed.

Because of the comparatively recent arrival of humans of European origin into the Pacific Northwest (PNW), there have been fewer plant introductions in this region than in many other areas of North America, and therefore much of the PNW remains relatively free of weeds (Reichard 2007). Despite this, invasive plants are a major problem in forests, rangelands, and parklands in the PNW. Invasive plants were estimated to infest 170,000 ha (420,000 ac) of U.S. Forest Service land in the PNW (USDA–FS 2005), and the U.S. Bureau of Land Management estimates that approximately 14 million ha (about 20%) of BLM-managed lands in the western states, not including Alaska, were infested with invasive weeds in 2000 (USDI–BLM 2016). Weeds infest an estimated 2.6 million ha of Oregon and Washington public lands, and this infestation has been growing at 10 to 15% annually. Prevention of new introductions, and control of those weed species already here, are high priorities for private landowners and government agencies throughout Canada and the United States (BCMFLNRO 2016; USDI–BLM 2016) and are particularly important to protect over 100 million ha of noninfested land in the PNW.

Weed control strategies have long been identified as mechanical (physical), cultural, biological, or chemical in nature (Anderson 1996). Combining two or more of these strategies into an integrated weed management program is considered more likely to succeed than implementation of any single weed-control strategy (Benz et al. 1999; Whitson et al. 1989). This is particularly true for invasive perennial plants. Integrated weed control programs on noncropland often include combination or sequential use of mowing/clipping/hand-pulling, controlled grazing, propane flaming/prescribed burns, herbicides, biological control agents, planting of competitive species, or fertilizer (DiTomaso 2000). As compared to foliar herbicide applications used alone, such integrated strategies can enhance the control of perennial weed species while potentially also reducing the amount of herbicide necessary to achieve a given level of management and thereby lessening the potential for herbicidal injury to adjacent desirable vegetation. As pointed out by Messersmith and Adkins (1995), however, the outcome of an integrated program depends on whether the interactions are antagonistic, additive, complementary, or synergistic. Synergistic interactions are the most desirable, but relatively few studies have been conducted

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Table 1. An overview of the integrated weed control strategies employed and the perennial weed species being managed as cited in this review article.

Integrated combination	Specific strategy	Perennial weed species
Mechanical + Chemical	Mowing, Tillage, and/or Burning + Herbicide	Canada thistle, leafy spurge, perennial pepperweed, knapweed (spotted and meadow), Japanese barberry, ironweed (western and tall), coralberry, common reed, and tropical soda apple
Mechanical + Chemical	Grazing + Herbicide	Spotted knapweed and leafy spurge
Mechanical + Chemical	Cut-Stem or Cut-Stump + Herbicide	Butterflybush, tree-of-heaven, European buckthorn, Russian-olive, Bohemian knotweed, Sakhalin knotweed, spurgelaurel, and indigobush
Biological + Chemical	Biological Control Insects or Pathogens + Herbicides	Leafy spurge and Canada thistle
Cultural + Chemical	Competitive Plants + Herbicides	Russian knapweed and Canada thistle
Cultural + Chemical	Fertilizers + Herbicides	Hawkweed (orange, meadow, and mouseear), oxeye daisy, chicory, slender bugleweed, dandelion, tall buttercup, shore horsetail, spotted knapweed, and yarrow
Mechanical + Biological	Mowing + Biological Control Insects	Leafy spurge
Biological + Cultural	Biological Control Insects + Competitive Plants	Canada thistle
Mechanical + Cultural	Mowing + Competitive Plants	Canada thistle

to test these interactions (Ainsworth 2003; Sciegienka et al. 2011).

An example of the development of an integrated management program in the PNW is for the relatively recent invader, wild chervil [*Anthriscus sylvestris* (L.) Hoffmann]. This short-lived perennial species was tested for sensitivity to herbicides following prebloom cutting and augmented with subsequent cultivation and seeding of a competitive perennial grass (Miller and D'Auria 2011). By combining mechanical (mowing and tillage), cultural (establishment of competitive vegetation), and chemical (specific herbicides) control strategies, wild chervil control was improved up to six-fold compared to herbicide treatment alone. This was obviously not the first integrated weed control program devised; rather, it is only a recent example from this region of the United States and adjacent Canada. Examining the literature for similar programs developed elsewhere is a beneficial pursuit because it could lead to new insights for control of problem perennial weeds in any region.

To that end, reports of various combinations of weed control strategies for use on perennial species known to be, or suspected to become, invasive in the PNW were compiled in this review article. The integrated weed management literature provides many examples of combinations of mechanical, cultural, biological, and chemical control strategies (Table 1). To facilitate comparisons of the successful integrated control strategies highlighted in this review, the following general categories are used: (1) Mechanical + Chemical, (2) Biological + Chemical, (3) Cultural + Chemical, (4) Mechanical + Biological, (5) Biological + Cultural, and (6) Mechanical + Cultural. Control of individual perennial weed species are discussed within these broad categories.

Mechanical + Chemical. This integrated strategy pairs herbage removal through mowing/clipping, burning, or grazing with herbicide application. Removal is most often accomplished prior to herbicide treatment, although mowing or grazing following herbicide application was also reported. Removing old or senesced foliage from previous growing seasons stimulates shoot growth in many perennial species, resulting in fresh leaf and stem tissues that are more receptive to herbicide uptake and translocation than older tissues. Such senesced foliage can also act as a physical screen to actively growing foliage within the canopy, so its removal usually improves herbicide deposition on the target weed or exposed soil. Finally, the onset of shoot growth can deplete root/crown energy reserves in the established perennial weed, leaving it more susceptible to herbicide activity.

Mowing, Tillage, and/or Burning + Herbicides. Treating with MCPB following mowing did not improve Canada thistle [*Cirsium arvense* (L.) Scop.] control in an Australian study (Amor and Harris 1977). In a Canadian study, however, 98% Canada thistle control resulted after rosettes were treated with a half-rate of glyphosate following late-July tillage (Hunter 1996). The enhanced control was

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attributed to a four-fold increase of glyphosate translocation into August rosettes compared with a June treatment at the bud stage of growth (Hunter 1995). Mowing before herbicide application did not consistently improve Canada thistle control in a Colorado study, mostly due to differences in water tables at the two test sites (Beck and Sebastian 2000). Mowing alone three times yr^{-1} for 2 consecutive yr at the subirrigated site decreased Canada thistle density 85%, but at the upland site, mowing failed to control Canada thistle. Improved control at the subirrigated site resulted when the two lowest recommended rates of clopyralid + 2,4-D were applied following two or three prior mowings, whereas at the upland site, two or three mowings only improved control when the highest rate of clopyralid + 2,4-D was used. Preapplication mowing at both sites resulted in only modest differences in Canada thistle control in autumn picloram or chlorsulfuron treatments, which provided uniformly excellent results (Beck and Sebastian 2000).

Although mowing alone slightly decreased leafy spurge (*Euphorbia esula* L.) density, application of picloram or 2,4-D to leafy spurge 16 and 35 d after mowing did not improve control of leafy spurge (Lym and Messersmith 1985). Control tended to decrease if herbicides were applied earlier than 35 d after mowing. To restore leafy spurge-infested range sites in Nebraska, a sequential combination of fall-applied herbicides followed by burning standing dead plant residue, then using no-till planting to re-establish desirable native tallgrasses in the spring was effective (Masters and Nissen 1998). Optimum herbicide combinations varied by tallgrass species, but subsequent suppression of leafy spurge growth was usually best in plots where grass biomass was greatest.

A similar program of autumn-applied herbicide followed by prescribed burning was tested in a long-term prairie restoration study in Washington (Stanley et al. 2010). The most disturbance-intensive treatment combination (sethoxydim application followed by prescribed burning and postfire glyphosate application) reduced the abundance of exotic grasses and forbs without negatively affecting native prairie species. Treatment with sethoxydim combined with fall mowing also aided in control of exotic grasses, but native species richness only increased in plots where native prairie species were subsequently seeded. The authors concluded that a variety of strategies based on the biology of weeds and desirable species, limiting conditions, and grassland ecology employed over several years will be instrumental toward achieving the objective of native prairie restoration.

Mowing followed by glyphosate application improved perennial pepperweed (*Lepidium latifolium* L.) control in California, whereas either mowing or glyphosate alone was ineffective (Renz and DiTomaso 1998). Subsequent trials showed that mowing reduced the number of aboveground perennial pepperweed meristematic sinks and increased the relative proportion of belowground sinks; removal of top growth also synchronized application timing with maximal translocation rates to root meristematic tissues (Renz and DiTomaso 2006).

Mowing followed by a low rate of clopyralid + 2,4-D gave 98% control of spotted knapweed (*Centaurea stoebe* L.), equivalent to picloram alone or picloram followed by hand-pulling (Brown et al. 1999). Hand-pulling for 2 yr gave 60% control, but mowing twice resulted in only about 30% control. Conversely, a single mowing of spotted knapweed at flowering or early seed production growth stage decreased mature plant density up to 85% (Rinella et al. 2001). The interactive effects of mowing, herbicides, hand-pulling, and burning on spotted knapweed control were studied in western Michigan (MacDonald et al. 2013). A single mowing or mowing followed by glyphosate did not provide lasting spotted knapweed control, but mowing once followed by clopyralid was effective for 4 yr. Hand-pulling spotted knapweed for 4 yr resulted in 94% control of adult plants and 97% control of seedlings. Low-intensity fire did not greatly affect spotted knapweed. Results demonstrated that persistent hand-pulling used as a follow-up to single mowing or mowing + herbicide treatments can be an effective practice for treating isolated spotted knapweed infestations or for removing the small numbers of knapweed that survive herbicide applications (MacDonald et al. 2013). Similarly, combinations of mowing and herbicide applications at rosette or early flowering stages of growth generally reduced meadow knapweed (*Centaurea debeauxii* Gren. & Godr.) biomass and increased grass biomass, although herbicide treatment alone achieved the same result (Miller and Lucero 2014). Mowing twice the previous year only provided 10% control. The authors concluded that mowing is not recommended to augment control of meadow knapweed when herbicides are used.

Japanese barberry (*Berberis thunbergii* DC) control was improved by initial mowing, propane flaming, or prescribed burning in late winter followed by treatment with glyphosate, triclopyr, or secondary propane flaming in early summer compared to mechanical treatments used alone (Ward et al. 2009, 2010). Mortality ranged from 20 to 40% for once-treated Japanese barberry bushes to 50 to 90% resulting from combination treatments, depending on initial bush size. The authors point out that initial and follow-up treatment selection depends upon the size of barberry clumps, the extent of the infestation, the goal of the treatment, site and personnel factors, and local regulations.

Mowing pastures infested with western ironweed (*Vernonia baldwinii* Torr.) and coralberry (*Symphoricarpos orbiculatus* Moench) prior to 2,4-D application improved western ironweed control compared with either mowing or herbicide alone (Peters and Stritzke 1969). Conversely, coralberry control was not increased by prior mowing, and application of nitrogen fertilizer did not improve control of either species. In a subsequent study, mowing in midsummer followed by triclopyr application in the autumn also effectively removed tall ironweed [*Vernonia gigantea* (Walt.) Trel.] from grass pastures (Marshall et al. 2006). In a recent study in Kentucky, aminopyralid + 2,4-D was evaluated with and without two annual mowings (before and after herbicide treatment) or two annual applications of ammonium nitrate (after herbicide treatment) for control of tall ironweed (Tolson et al. 2012). Herbicides reduced tall ironweed stem density by 64 to 89% by 9 mo after treatment (9 MAT), but mowing alone, fertilizer alone, or mowing + fertilizer did not reduce tall ironweed populations, except at one location where mowing alone reduced tall ironweed stems by 64%. These results were short-lived, however, because tall ironweed control was similar for all treatments at two sites by the second year, although at a third site herbicide combined with mowing or fertilizer reduced tall ironweed stems by 78%. Importantly, forage biomass on treated pastures was maximized by the herbicide + fertilizer and mowing + herbicide + fertilizer.

Cutting of common reed [*Phragmites australis* (Cav.) Trin. ex Steud.] during anthesis followed by application of glyphosate the following spring improved control at 3 MAT compared with cut-only plants or to intact plants treated with glyphosate (Monteiro et al. 1999). In a subsequent study, Derr (2008) applied glyphosate either 1 mo after mowing or 2 wk prior to mowing and obtained 86 and 90% control, respectively, at 12 MAT compared to glyphosate applied to nonmowed common reed (81% control). Biomass of glyphosate-treated common reed at 12 MAT was similar whether plants were mowed or not, however, ranging from 88 to 94% reduction as compared to nontreated plants.

The effectiveness of triclopyr on tropical soda apple (*Solanum viarum* Dunal) was improved by first mowing plants to 7.5 cm (3 in) and spraying regrowth 60 d later (Mislevy et al. 1997). A second application of triclopyr provided better control than did a single triclopyr application for both mowed and nonmowed treatments. Mowing tropical soda apple two times prior to triclopyr application also aided control (Mislevy et al. 1999). A single mowing prior to herbicide application resulted in 28% control, whereas two or three mowings at 60-d intervals resulted in 82 and 84% control, respectively.

Grazing + Herbicides. The combination of 2,4-D application followed by sheep grazing reduced spotted knapweed rosette density by 99%, compared to reductions of 44 and 28% for grazing or 2,4-D alone, respectively, after 3 yr (Sheley et al. 2004). The authors pointed out that spring herbicide applications improved spotted knapweed palatability, resulting in preferential grazing by sheep. When only 2,4-D was used, density of flowering spotted knapweed plants increased from 3.7 to 10.7 m^{-2} (40 to 115 ft^{-2}) after 4 yr, while density did not increase in 2,4-D + sheep grazing treatment.

Grazing followed by fall herbicide application reduced leafy spurge density more quickly and maintained the lower density longer than either method used alone (Lym et al. 1997). Continuous grazing more quickly removed leafy spurge than rotational grazing. Up to 98% control at 3 yr after treatment was achieved by a single fall application of picloram + 2,4-D, either to nongrazed plants or after spring grazing.

Cut Stem or Cut Stump + Herbicides. This integrated strategy consists of mechanical removal of woody stems followed by direct application of phloem-mobile herbicides to freshly exposed cambial tissue, enhancing herbicide uptake and translocation to active sites within the plant. Such applications are less affected by wind and rain than are foliar applications and can be equally effective on actively-growing or dormant weeds, thus appreciably expanding the treatment season. Herbicide application to tall trees/shrubs is also more efficient using this method than attempting to apply herbicide to the leaf canopy, particularly if backpack application equipment is being used. Although herbicide concentration is greater than would be used for foliar application, overall product usage can be less than that for foliar applications if woody weeds are large or not growing in dense population.

Foliar applications of glyphosate more quickly defoliated butterflybush (*Buddleja davidii* Franch.) than did triclopyr and imazapyr, although cut-stump applications with these herbicides provided more rapid control than foliar applications (Altland and Ream 2010). Imazapyr and triclopyr ester applied as cut-stump treatments were more effective than glyphosate or triclopyr amine, whereas foliar applications were generally inadequate for butterflybush control (T. Miller, C. Lucero, A. Peters, unpublished data). Cutting alone did not provide adequate control of butterflybush in either trial.

Cutting alone also did not control tree-of-heaven [*Ailanthus altissima* (Miller) Swingle], but cut-stump treatment with imazapyr or triclopyr ester reduced regrowth by 90% (DiTomaso and Kyser 2007). Stem injection (also known as hack-and-squirt) with undiluted imazapyr or glyphosate reduced tree-of-heaven canopy by 95 and 92%, respectively. The authors noted that stem removal at 4, 8, or 12 MAT did not reduce imazapyr effectiveness. Basal bark treatments with imazapyr or triclopyr ester (20% v/v in oil) gave nearly complete control (DiTomaso and Kyser 2007). Basal bark (triclopyr ester), stem injection (picloram + 2,4-D), and stem injection with glyphosate using an EZ-Ject® lance (ArborSystems, P.O. Box 34645, Omaha, NE 68134) treatments provided 91 to 100% top kill (Bowker and Stringer 2011). Treatments resulted in 3 to 12% and 0 to 2% resprouting in 2006 and 2007, respectively, except for the glyphosate EZ-Ject treatment, which resulted in 33 and 5% regrowth, respectively.

Cut-stump and basal bark treatments with triclopyr ester gave good control of European buckthorn (*Rhamnus cathartica* L.), with a 120-fold reduction in seed production resulting from two herbicide applications over 6 yr (Delanoy and Archibold 2007). The authors suggest that three herbicide applications should nearly eliminate European buckthorn from a site, although they estimated that the cost those treatments could exceed \$3,400 ha^{-1}.

Cut-stump applications of imazapyr, triclopyr, picloram, glyphosate, and 2,4-D + dicamba controlled 100% of Russian-olive (*Elaeagnus angustifolia* L.) at 12 MAT, compared to 40% control of trees that were cut only (Nielsen and Wilson 2009). Control was equally effective in spring or autumn. Triclopyr applied as cut-stump treatments in Dinosaur National Monument reduced saltcedar (*Tamarix ramosissima* Ledeb.) by 74% and Russian-olive by 89% from 2002 to 2010 (Stoker et al. 2011). Aminocyclopyrachlor was also shown to be effective for cut-stump applications to Russian-olive (Lym 2010). Russian-olive and saltcedar mortality with metsulfuron + aminocyclopyrachlor was over 90% when applied as a cut-stump treatment compared to 70 to 90% canopy reduction resulting from foliar treatments (Brock 2011). However, Getts and Westra (2014) warn that the radius of inhibition to nontarget vegetation around treated Russian-olive stumps was greater with aminocyclopyrachlor than with glyphosate, triclopyr, or imazapyr (26, 4, 8, and 13 cm, respectively) at 30 MAT.

Invasive knotweed (*Polygonum* spp.) is usually treated using foliar applications of glyphosate, imazapyr, or triclopyr or stem injection with glyphosate (Davenport 2006; Miller 2004, 2007; Prather et al. 2009). An integrated practice for knotweed control was developed by The Nature Conversancy that entails bending tall knotweed stems in early summer, followed by foliar herbicide application to knotweed regrowth about 3 wk later. Bending reduces the height of the knotweed canopy, allowing for more efficient herbicide application using a backpack sprayer (Davenport 2006). Mowing or bending stems 4 wk prior to herbicide application resulted in quicker defoliation of Bohemian [*Polygonum* × *bohemicum* (J. Chrtek & Chrtková) Zika & Jacobson] and Sakhalin knotweed (*Polygonum sachalinense* F. Schmidt ex Maxim.), although control at 12 MAT was not improved compared to treatment with herbicide alone (Miller 2004, 2007).

Cut-stem applications of aminopyralid, aminocyclopyrachlor, glyphosate, imazapyr, and triclopyr ester + 2,4-D ester provided control of spurgelaurel (*Daphne laureola* L.), while aminopyralid, clopyralid, glyphosate, and imazapyr also gave control of indigobush (*Amorpha fruticosa* L.) (T. M. Miller, unpublished data).

Biological + Chemical. Classical biological control programs include the release of insects or disease pathogens that parasitize weeds, reducing their vigor and/or reproductive capacity. As Piper (2004) observed, biological control agents must have living plants on which to develop and reproduce, and employing other management strategies prior to agent release could disrupt target weed growth to a degree that agents might fail to establish. Consequently, herbicide applications prior to agent release are often discouraged. The concept of combining biological control agents with herbicides for invasive weed control has been discussed in some detail (Ainsworth 2003; Messersmith and Adkins 1995). Although herbicides can be directly toxic to a biological control insect or may destroy its food supply, they can also enhance host plant nutritional quality or result in the host plant population being in a stage of growth more conducive for agent attack at the time of release (Messersmith and Adkins 1995). Biological and chemical control can be successfully integrated to improve control of perennial weed species; however, careful planning is required.

Biological Control Insects or Pathogens + Herbicides. Perhaps the first systematic studies of this integrated strategy were conducted on leafy spurge, as reviewed by Lym (2005).

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The leafy spurge hawkmoth (*Hyles euphorbiae* L.) was successfully introduced in North Dakota in the 1970s but was unable to adequately slow the spread of leafy spurge, necessitating the subsequent application of herbicide. Hawkmoth larvae were found to tolerate both 2,4-D and picloram, provided the herbicides were applied in the fall after hawkmoth larvae were in the fourth or fifth instar stage (Reese and Fay 1989). Another biocontrol insect, the leafy spurge gall midge (*Spurgia esulae* Gagné), was also found to tolerate imazethapyr, picloram, and 2,4-D applications if 15 to 20% of the leafy spurge remained untreated (Lym and Carlson 1994).

One of the most positive results of combinations of biological and chemical control on leafy spurge was from an anecdotal report provided by Lym (2005). A site where the leafy spurge flea beetle (*Aphthona nigriscutis* Foudras) had been released 2 yr previously was accidentally treated with picloram + 2,4-D. The inadvertent application resulted in improved leafy spurge control and an increase in the *A. nigriscutis* population. A subsequent study documented that leafy spurge control was more rapidly achieved when *Aphthona* spp. were used in combination with herbicide application (Lym and Nelson 2002). In addition, acceptable leafy spurge control was found to last up to 5 yr from a single herbicide application. Releasing *Aphthona* spp. 1 yr after imazapic application was later shown to enhance flea beetle establishment and population development (Joshi 2008).

The three-way interaction between the stem-mining weevil (*Hadroplontus litura* F.), the pathogen *Pseudomonas syringae* pv. *tagetis* (PST), and glyphosate was recently quantified for Canada thistle (Sciegienka et al. 2011). Application of the pathogen prior to the release of weevil larvae could be more deleterious to Canada thistle than a late application. The authors also found a slight antagonistic interaction between glyphosate and pathogen, but concluded that the three-way interaction was mostly additive in nature.

Cultural + Chemical. Cultural methods of weed control have been defined as maintenance practices that make it difficult for weeds to grow or become established (Anderson 1996) and include use of competitive plants, fertilizer applications, supplemental irrigation, grazing programs, and other managerial activities designed to make a plant community more resistant to weed invasion and competition. Optimally, herbicide applications put weeds at a disadvantage compared to other vegetation on the site and, when coupled with seeding of competitive plant species or fertilizing desirable vegetation already present, the resulting plant community is more vigorous and can limit weed growth and delay or prevent reinfestation of the treated site.

Competitive Plants + Herbicides. Integration of herbicides with establishment of well-suited perennial grasses has been shown to more effectively control Russian knapweed [*Acroptilon repens* (L.) DC.] and leafy spurge (Christianson et al. 1994; Ferrell et al. 1992, 1995; Whitson et al. 1989, 1993). An early trial showed that picloram controlled spotted knapweed and provided a "good knapweed kill" while allowing a crested wheatgrass [*Agropyrum cristatum* (L.) Gaertn.] seeding to successfully establish and increase forage yield for the site (Hubbard 1975). Other perennial grass species have also been widely tested on western rangelands, including Russian wildrye [*Psathyrostachys juncea* (Fisch.) Nevski], thickspike or streambank wheatgrass [*Elymus lanceolatus* (Scribn. & J. G. Smith) Gould], pubescent wheatgrass [*Agropyron intermedium* (Host.) Beauv. var. *trichophorum* (Link) Halácsy], and western wheatgrass [*Pacopyrum smithii* (Rydb.) A. Love]. Use of these grasses to aid in control of Russian knapweed, although generally favorable, has met with mixed results. These grasses seeded in the absence of herbicide pretreatment accounted for 23 and 25% Russian knapweed control in tilled and nontilled plots, respectively, after 3 yr (Bottoms and Whitson 1998). With a single application of picloram or two applications of clopyralid + 2,4-D prior to grass seeding, however, Russian knapweed control was increased to as much as 87%. Burning, mowing, and metsulfuron treatments did not adequately control Russian knapweed in these trials. In another study, Russian knapweed was controlled 66 to 93% by clopyralid + 2,4-D + seeded grasses at 2 yr after treatment, compared to only 7% Russian knapweed control from the herbicide treatment alone (Benz et al. 1999). Glyphosate + thickspike wheatgrass resulted in 36% Russian knapweed control, whereas glyphosate applied alone tripled Russian knapweed growth and glyphosate + crested wheatgrass, Russian wildrye, or streambank wheatgrass increased Russian knapweed growth 1.5, 2, and 1.6-fold, respectively. Metsulfuron + streambank wheatgrass controlled 61% of Russian knapweed whereas metsulfuron applied alone provided 40% control. Conversely, mowing alone was ineffective and mowing + crested wheatgrass doubled Russian knapweed growth.

Canada thistle control after 3 yr was greater than 90% where perennial grasses had been established following tillage (Wilson and Kachman 1999). Competitive grasses alone were as effective as yearly applications of clopyralid at 0.55 kg ha^{-1} (0.5 lb ac^{-1}) for controlling Canada thistle.

Fertilizers + Herbicides. Combining herbicide with fertilization has been tested on pastures infested with many perennial weed species. One of the first trials was conducted by Hay and Ouellette (1959) in eastern Canada where 2,4-D was sprayed on pastures infested by several broadleaf weed species. Orange hawkweed (*Hieracium aurantiacum* L.), kingdevil hawkweed (*H. piloselloides* All.), mouseear hawkweed (*H. pilosella* L.), oxeye daisy (*Leucanthemum vulgare* Lam.), chicory (*Cichorium intybus* L.), and slender bugleweed (*Lycopus uniflorus* Michx.) were decreased when 56–67–101 kg ha^{-1} of $N–P_2O_5–K_2O$, respectively (no fertilizer formulation provided) was added, but dandelion (*Taraxacum officinale* G. H. Weber ex Wiggers), Canada thistle, tall buttercup (*Ranunculus acris* L.), shore horsetail (*Equisetum litorale* Kühlewein), wild strawberry (*Fragaria virginiana* Duchesne), and common yarrow (*Achillea millefolium* L.) populations remained unchanged. Fertilizer application also improved the quantity and quality of forage as 2-4-D reduced broadleaf weed presence. Total vegetative yield was not increased when weeds were controlled by 2,4-D, but forage from treated plots consisted almost exclusively of desirable grasses. Best results from the standpoint of both yield and absence of weeds were obtained when fertilizer treatment was supplemented by applications of 2,4-D.

Mouseear hawkweed cover was decreased 90% after application of ammonium phosphate fertilizer (200 kg ha^{-1} 18-46-0 nitrogen–phosphorous–potassium [N–P–K]) in nongrazed pasture after 2 yr (Cipriotti et al. 2011). Fertilized, grazed plots did not show a similar decrease in mouseear hawkweed, but application of 2,4-DB ester gave about 60% control regardless of grazing. The authors concluded that a control strategy based on the use of selective herbicide with fertilizer, coupled with a transient ban on sheep grazing, resulted in good control of mouseear hawkweed and aided in restoring native vegetation.

Applications of selective broadleaf herbicides in combination with ammonium nitrate were shown to be effective for controlling Canada thistle, although fertilizer applied in the absence of thistle control resulted in excessive Canada thistle growth (Hay and Ouellette 1959; Reece and Wilson 1983). Grekul and Bork (2007) found that 2,4-D, 2,4-D + mecoprop + dicamba, clopyralid, and picloram + 2,4-D applied with fertilizer improved Canada thistle control in a pasture in Alberta, whereas fertilizer alone simply increased Canada thistle density 1 yr after treatment.

Spotted knapweed control was enhanced through the release of residual perennial grasses by herbicide applications and fertilizer treatment (Hubbard 1975; Sheley et al. 1984). Picloram applied alone increased grass yield to 660 kg ha^{-1} from about 275 kg ha^{-1} in nontreated plots, whereas the combination of fertilizer with picloram resulted in 2,200 kg ha^{-1} 2 yr after the applications (Sheley and Roche 1982). In a subsequent study, picloram used alone reduced spotted knapweed density to nearly zero and increased grass yield by an average of 1,500 kg ha^{-1} (Sheley and Jacobs 1997). Fertilization did not affect spotted knapweed density, but the highest rates increased grass yield on those sites with a substantial residual grass understory, indicating that applying fertilizer–picloram combinations can be a successful strategy for sites with mixed spotted knapweed and desirable grasses. Midsummer 2,4-D and 32–0–0 N–P–K applications at 1.1 kg and 150 kg ha^{-1}, respectively, also provided effective spotted knapweed control and increased resident grass production but did not detrimentally affect native forbs along riparian corridors in Montana where residual herbicide use was not advisable (Jacobs and Sheley 1999).

Mechanical + Biological. These two strategies appear to be best utilized when grazing follows successful introduction of biological control insects on the target weed species. Grazing must be carefully timed to avoid harming insect survivability (Piper 2004). Insect feeding can leave the weed more palatable to livestock, and properly-timed grazing can reduce weed seed production, results that combine to reduce weed population.

Grazing + Biological Control Insects. Leafy spurge flea beetles have been shown to be more effective when used in sequence with livestock grazing. Grazing sheep on leafy spurge-infested lands where *Aphthona* spp. had been previously established reduced leafy spurge stem density and cover more than either strategy used alone (Beck and Rittenhouse 1999, Hansen 1993; Samuel et al. 2004). Sheep grazing, coupled with flea beetle release, more quickly reduced leafy spurge stem density than *Aphthona* alone, and leafy spurge biomass was reduced by grazing alone (Samuel 2003). Implementation of this combination also resulted in the treated pasture being able to subsequently support more cattle than either rotational grazing with sheep or with *Aphthona* spp. used alone. Integration of sheep with *Aphthonia flava* Guillebeau provided effective leafy spurge management in sensitive areas where herbicide use was very limited (Beck and Rittenhouse 2000).

Biological + Cultural. Biological control agent release is designed to reduce the vigor of the host plant, making it less likely to spread or reproduce. Other vegetation on the site can then compete more effectively with the negatively impacted weed species and this leads to a reduction in the weed population. If the population of desirable vegetation on the site is limited or nonexistent, biological agent effectiveness can be complemented by concurrent establishment of competitive plant species. Presence of desirable plant species on the site also reduces the likelihood that a different weed species will invade in the future.

Biological Control Insects + Competitive Plants. Canada thistle biomass was reduced approximately 70% by the combination of the thistle tortoise beetle (*Cassida rubiginosa* Müller) and seeding with tall fescue [*Lolium arundinaceum* (Schreb.) S. J. Darbyshire] or trailing crownvetch (*Coronilla varia* L.) (Ang et al. 1994). Canada thistle biomass at 3 yr after seeding was minimized when the beetle population was at least 50 beetles m^{-2} and crops were seeded between 1.2 and 1.25 times the recommended rate of 20 kg ha^{-1} of crown vetch and 50 kg ha^{-1} of tall fescue.

Mechanical + Cultural. Although invasive perennial weeds can be damaged by mechanical efforts, rarely does full control result from that strategy alone. If, however, a desirable plant species is present that sustains less damage from mechanical control than does the weed, that species can more effectively compete with the weed and thereby increase its relative abundance on the site. It must be remembered that mowing, fire, grazing, or cultivation are relatively nonselective tools and can be as or more harmful to the desirable species as to the weed. Therefore, only those mechanical control techniques favoring the desirable species and negatively affecting the weed species should be employed in this integrated strategy.

Mowing + Competitive Plants. Mowing combined with competition from tall fescue resulted in a 60 to 70% reduction in Canada thistle density (Thrasher et al. 1963), while smooth bromegrass (*Bromus inermis* Leyss.) coupled with mowing for 3 yr provided over 90% suppression of Canada thistle (Derscheid et al. 1961). Wilson and Kachman (1999) found that seeding a Canada thistle-infested pasture with intermediate wheatgrass, hybrid wheatgrass (*Elymus hoffmannii* K.B. Jensen & K.H. Asay), western wheatgrass, Russian wildrye, and tall fescue and then mowing twice per year for 3 yr controlled over 90% of Canada thistle.

Future Directions

The literature is rich with examples of excellent results obtained through use of integrated weed management strategies. Still, there are areas where further work may build on these promising beginnings. One such area is the use of biological control insects with subsequent herbicide applications. Although not an invasive plant outside of cultivated ground, insect predation of volunteer potato (*Solanum tuberosum* L.) by the Colorado potato beetle (*Leptinotarsa decemlineata* Say) reduced the herbicide dose required for volunteer potato control to 65 to 85% of what would be required in the absence of the insect (Williams et al. 2004). Targeting volunteer potato control with fluroxypyr immediately prior to periods of high herbivory was most effective in these trials. Similar herbicide rate reductions resulting from insect herbivory on invasive plant species would be an attractive alternative for many land managers. Given the successes in leafy spurge control from biological control agent release with subsequent herbicide application (Lym and Carlson 1994; Lym and Nelson 2002), additional research along this line with various other weed species would be warranted.

A second topic for further investigation involves soil carbon (C) addition in combination with other weed management strategies for native community restoration. Blumenthal et al. (2003) showed that immobilization of soil nitrogen (N) through addition of C was more beneficial to native prairie species in Minnesota than to nonnative weedy species. Sucrose and sawdust additions were on the order of 1,350 g m^{-2} (4.4 oz ft^{-2}) in their experiments, but the authors postulated that on low-N sites, use of other management techniques such as mowing or burning can reduce the amount of C addition necessary to enhance native species establishment and achieve good weed control. Although these studies focused on weed seedlings, it is possible that implementation of biological or chemical control might also negatively impact established perennial weeds enough to reduce the quantity of C addition necessary to elicit the positive response of native species on western grasslands. Vasquez et al. (2008) similarly argue that low soil N benefits mid- and late-seral species and discourages invasion by weedy annuals, downy brome (*Bromus tectorum* L.) in particular. Such multitiered strategies, those coupling chemical or biological weed control efforts with active management of soil N and C, are worth exploring to reduce the cost and improve the successful re-establishment of native forbs and grasses on perennial weed-infested sites in the PNW and beyond.

Conclusion

DiTomaso (2000) wrote that development of a long-term strategic plan for noxious weed management on

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rangelands must incorporate elements of prevention and educational materials and activities with multiyear, integrated management. If thoughtfully crafted, carefully applied, and diligently maintained, integrated strategies can reclaim infested lands and stabilize degraded ecosystems, making the plant community more resistant to invasion by other invasive plants.

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