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# Integration of Chemical Control with Restoration Techniques for Management of *Fallopia japonica* Populations

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## Abstract

Effective management of invasions by *Fallopia japonica* are currently limited to repeated annual herbicide applications and research efforts are needed to determine integrated cost-effective treatments that result in greater management success. We evaluated several different herbicides for *F. japonica* control in the greenhouse and under field conditions and coupled chemical control with restoration activities at an invaded site. Results suggest that: 1) glyphosate applied at 4.21 kg ae/ha is the most cost effective treatment option, 2) the standard rate for *F. japonica* control with aminocyclopyrachlor is approximately equivalent to the 0.56 kg ai/ha, 3) restoration with grasses can be coupled with targeted chemical control.

## Keywords

*Invasive species, native plants, weed management*

## Bio-sketch

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## Introduction, Hypotheses and Problems for Management

*F. japonica* (Houtt.) Ronse Decraene is a widely distributed rhizomatous perennial with shrub-like herbaceous growth that dies back yearly in cold climates. It is native to Asia and is commonly found in riparian areas, coastal habitats, roadsides, and unmanaged areas of North America and across Europe (Bashtanova et al. 2009; Bourchier & Van Hezewijk 2009). Infestations are extremely difficult to manage and over time native plant diversity and abundance diminish when an ecosystem becomes dominated by *F. japonica* (Fig. 1). Correlated with this change in plant diversity is a total reduction in invertebrate abundance and species richness (Gerber et al. 2008). This reduction in arthropod abundance also leads to infestations negatively impacting foraging success of insectivorous species (Maerz et al. 2005).

**Fig. 1**. Dense infestation of *F. japonica* growing in a floodplain of a coastal river watershed in western Oregon, U.S., with very few other plant species established under the *F. japonica* canopy .

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In addition to these detrimental characteristics that make *F. japonica* an undesirable invasive plant in many ecosystems, it is also very resilient to chemical control (Bashtanova et al. 2009), which is currently the only practical management tactic used by most weed management personnel in many areas in the U.S.A. (Hulting Personal Observation). Although extensive chemical management of *F. japonica* is occurring throughout the Pacific Northwest (PNW) of the U.S.A. there is little information available indicating which herbicide application methods and active ingredients will result in the greatest management success. Chemical control of this species is problematic for many reasons including difficultly in timing herbicide applications for maximum control with respect to plant growth stage and environmental conditions, lack of information on most effective active ingredients for control, tolerance to herbicide active ingredients, the need for repeated annual herbicide applications and because *F. japonica* will establish in sensitive habitats, such as riparian areas, where the use of some herbicides may be restricted. Herbicides labelled for aquatic use are typically used for treatment of *F. japonica* populations adjacent to surface water. The most commonly used herbicide active ingredients in the PNW include foliar applications of glyphosate (Rodeo®, Aquamaster®) and imazapyr (Habitat®) (Hulting Personal Observation).

Many sites invaded by *F. japonica* sites are ecologically degraded or disturbed prior to infestation. Restoration of these invaded sites in the PNW to a functioning riparian plant community after herbicide treatment is needed to prevent re-infestation by *F. japonica* or other invasive weed species. There is little information available on successful restoration techniques for chemically treated sites. Due to the difficulty in eradicating infestations and necessity to repeat annual herbicide treatments, replanting of native species frequently does not occur. However, vegetation surrounding treated sites can quickly re-colonize many sites (Ford 2004; Miller 2005). While this can result in desirable native plants being restored to the site (Ford 2004), the possibility for undesirable plant species to re-infest the area is also a management concern.

Restoration to ecologically desirable species may increase the resilience of these sites to future infestations. A diverse mixture of native tree and shrub species is most suitable for riparian sites in the PNW, but it is difficult to restore a site dominated by *F. japonica* to these species due to the altered site conditions caused by *F. japonica*

## Resumen

El manejo efectivo de las invasiones de *Fallopia japonica* está actualmente limitado a la aplicación anual repetida de herbicidas, y se necesita realizar esfuerzos de investigación para determinar los tratamientos integrados con mejor balance coste-efectividad que conllevan un mayor éxito en el manejo. En este trabajo evaluamos diferentes herbicidas para el control de *F. japonica* en invernadero y condiciones de campo, y acoplamos el control químico con trabajos de restauración en las parcelas invadidas. Los resultados sugieren que: 1) el glifosato aplicado a razón de 4.21 kg equivalentes ácido/ha es la opción con mayor balance coste-efectividad, 2) la tasa estándar para el control de *F. japonica* control con aminocyclopiraclor es de 0.56 kg ai/ha, 3) la restauración con herbáceas perennes puede ser acoplada a un los trabajos de control químico.

## Palabras clave

*Especies invasoras, plantas nativas, manejo de malas hierbas o malezas*

including physical blocking of ambient sunlight, development of and changes in soil pathogen communities, allelopathic interference (Siemens & Blossey 2007), and because of a general homogenizing effect on soil physical and nutrient properties (Dassonville et al. 2007) coupled with the need for repeated herbicide applications to control *F. japonica*. Establishment of a transitional plant community may act as a restoration stepping stone eventually allowing managers to direct the invaded site towards a more desirable state.

An experiment was initiated to investigate the integration of F. *japonica* management and restoration activities. This multi-year field study was conducted in a *F. japonica* infestation on the coastal Nehalem River near Garabaldi, Oregon, U.S.A. (Figs. 2a and 2b). The objective of this field research was to integrate the planting of PNW native grasses with herbicide treatments to reduce *F. japonica* biomass and to establish a native grass plant community at the invaded site. We hypothesized that we could establish a grass community in an infested area that was undergoing herbicide treatment to reduce weed biomass, and that grass community could be managed as a stepping stone plant community which could later be restored to mixed tree and shrub species. The efficacy of both restoration methods and herbicide control was quantified in this study through the implementation of the native grass seeding and herbicide efficacy field studies described below. We also hypothesized that the new herbicide active ingredient, aminocyclopyrachlor, may be a useful chemical tool to manage *F. japonica* in the future. A greenhouse study was conducted to quantify the potential of this new herbicide active ingredient for *F. japonica* control.

## Methods

### *Native Grass Establishment*

Field studies were initiated in the spring of 2008 and continued through fall of 2009 with the purpose of determining the establishment success of native grass species in a *F. japonica* infestation subjected to herbicide treatment. This study was designed to investigate two different grass seeding rates. The experimental design of this study was a complete randomized block with split plots.

**Fig. 2**. Location of experimental studies where a large infestation of *F. japonica* grows along the Nehalem River near Garabaldi, Oregon, U.S.A. shown here in spring (2a) and during the winter months (2b) after leaf drop with only primary canes of plants remaining after flooding events at the site.

Each of the four randomized complete blocks contained five 9 $m^2$ plots. Each 9 $m^2$ plot was subdivided into three 3 $m^2$ subplots (control and two grass seeding rates). Grass species were chosen based on the local availability, potential cost, desirability and competitiveness of the species, and the species suitability to variable environmental conditions at the field site. The native grass species mixture adapted to the local environment and selected for this study was made up of the following species: *Elymus glaucus*, *Hordeum brachyantherum*, *Bromus carinatus*, *Deschampsia cespitosa*, and *Deschampsia elongata*. These grass species were not present at the site prior to the initiation of this experiment, but are endemic to the general study area. The two *Deschampsia* sp. made up 10% of the mix by weight with the remaining three species comprising the other 90% of the mixture.

The native grasses were hand-seeded and lightly raked into the moist soil of the *F. japonica* infested plots at two rates (10 kg/ha and 40 kg/ha) on May 1, 2008. *F. japonica* plants were just beginning to emerge from underground rhizomes on this date. Grass establishment was initially evaluated by visually estimating percent grass cover 30 days after seeding (DAS) and measuring grass seedling density 45 DAS (Fig. 3). Grass survival was evaluated by measuring grass plant density 176 DAS.

**Fig. 3**. Grass seedling density was quantified after seeding under the *F. japonica* by using quadrat counts.

*Statistical Analysis*

Separate linear regression models were used for both of the grass density measurements and for the percent cover data that included both the seeding rate and experimental block as explanatory variables. Ninety-five percent individual confidence intervals were calculated for the treatment means (Rinella & James 2010).

*Herbicide Efficacy Field Studies*

The *F. japonica* growing in the experimental plots used to evaluate native grass establishment were treated with one of four different single herbicide applications during the fall of 2008. These foliar herbicide applications included glyphosate applied at 4.21 kg ae/ha, imazapyr at 1.12 kg ae/ha, triclopyr at 10.1 kg ae/ha, and 2,4-D at 4.26 kg ae/ha, all applied at a total spray volume of 2243.2 L/ha. Glyphosate and imazapyr were chosen because these active ingredients (hereafter 'ai') are currently the standard *F. japonica* control herbicides used by many land managers. Triclopyr and 2,4-D were chosen based on the selectivity of the products and their potential to cause less injury to the newly established grass plants compared to the glyphosate and imazapyr treatments.

In addition to this experiment that combined testing grass establishment and herbicide treatment an additional study was conducted on separate experimental plots to determine the efficacy of three herbicide tank mixtures for *F. japonica* control. Herbicide combinations applied to these experimental plots included glyphosate with imazapyr, imazapyr with aminopyralid, and triclopyr with 2,4-D. The application rates of these products were imazapyr applied at 1.12 kg ae/ha, glyphosate at 4.21 kg ae/ha, aminopyralid at 0.12 kg ae/ha, triclopyr at 10.1 kg ae/ha, and 2,4-D at 4.26 kg ae/ha.

The imazapyr tank mixtures were evaluated because anecdotal evidence suggested synergistic effects between these compounds when used on *F. japonica*. The triclopyr and 2,4-D mixture was evaluated because of the current lack of efficacy data on this mixture when used on *F. japonica* and the previously documented high efficacy of this treatment on other invasive, woody broadleaf perennial plants (Hulting Personal Observation).

All herbicide treatments were applied with a $CO_2$ pressurized backpack sprayer equipped with a high-pressure spray gun and adjustable nozzle on October 13, 2008 (165 DAS). During the herbicide application the *F. japonica* plants were sprayed from all four sides of experimental plots resulting in all aboveground plant parts (both the top and underside of leaves and all sides of canes) being sprayed with the herbicide solution until covered.

Plots were visually evaluated for percent injury (% of plants exhibiting herbicide symptomology compared to an untreated control) to *F. japonica* during the same growing season as the herbicide treatment prior to normal senescence and leaf drop of the treated plants; 11 days after treatment (DAT) and 32 DAT. Percent injury to *F. japonica* was also evaluated during the next growing season (2009) at seven and 12 months after treatment (210 DAT and 378 DAT). Reduction in *F. japonica* biomass was evaluated by measuring new shoot density, height, and diameter at approximately 25 centimeters aboveground six months after treatment (196 DAT).

### *Statistical Analysis*

A linear regression model was used for each *F. japonica* injury and biomass data set that included both the herbicide treatment and experimental block as explanatory variables. Ninety-five percent individual confidence intervals were calculated for the treatment means.

### *Aminocyclopyrachlor Efficacy Greenhouse Study*

Greenhouse experiments were conducted at the Oregon State University Crop and Soil Science greenhouses using clones propagated from plant cuttings. Rhizomes were hand pulled or dug from the surface soil of *F. japonica* populations in the Luckiamute Watershed (southern Polk County, Oregon, U.S.A.) in the fall of 2007. These harvested rhizomes were divided and planted in Sunshine Professional Growing Mix™ potting soil in the greenhouse to be used as a source of cutting materials for the propagation of clones used in the greenhouse herbicide efficacy trial. Clones were used in greenhouse experiments due to the unavailability of *F. Japonica* seeds that could be used for plant propagation. Although the use of shoot cuttings to produce plants resulted in reduced genetic variation in our experimental groups, this experimental population appropriately represents a model of the clonal *F. japonica* populations targeted for herbicide treatment in the field.

Clones were propagated from young *F. japonica* shoot cuttings. The diameter of cuttings used for propagation was under 1 cm and their length was approximately 16 cm. Each cutting included at least one stem node and one leaf. The basal end of the cutting was dipped in rooting powder (Rootone™ containing: 0.20% 1-Naphthalene-acetamide, 4.04% Thiram [tetramethyl-thiuram-disulfide] and 95.76% inert ingredients) and planted into moist potting soil. The cuttings were transplanted to 2.8 L containers after 6 wk of growth. The plants were approximately 0.5 m tall and had grown for 11 weeks prior to herbicide treatments (Fig. 4). Greenhouse temperature was maintained at an average nighttime temperature of 18.4°C and an average daytime temperature of 20.1°C and day length was extended to 14 hours through the use of supplemental lighting. Plants were watered and fertilized as needed, typically watered three times per week and fertilized once per month with Miracle Gro™ all-purpose plant food (15-30-15 with micronutrients).

**Fig. 4**. Greenhouse grown *F. japonica* plants used in the efficacy study.

Three separate herbicide efficacy experiments were conducted that each included control plants and plants treated with the standard rates of imazapyr and glyphosate (1x rates were 0.84 kg ae/ha for imazapyr and 3.37 kg ae/ha for glyphosate, plus 1% v/v crop oil concentrate) and combinations of aminocyclopyrachlor rates (plus 0.25% v/v non-ionic surfactant). Experiment A was initiated on August 8, 2008, and included aminocyclopyrachlor applied at 0.07, 0.14, 0.28, kg ai/ha rates. Experiment B was initiated on November 25, 2008, and included aminocyclopyrachlor applied at 0.035, 0.14, 0.56 kg ai/ha rates. Experiment C was initiated on June 25, 2009, and included aminocyclopyrachlor applied at five treatment rates including 0.035, 0.07, 0.14, 0.28, 0.56 kg ai/ha. For each of the experiments an experimental unit consisted of three plants and each treatment was replicated three times.

Data collection included visual evaluation of the percent control of *F. japonica* (the percent of injury observed when compared to the control plants) evaluated at 7, 21, and 63 days after treatment (DAT). Above ground biomass was clipped 70 DAT dried and weighed. The dry weight of each plant was converted to percent of control dry weight by dividing each measured value by the average control dry weight (percent of control dry weight = dry weight of plant/mean dry weight of control). This clipping and weighing process was repeated after re-growth of the treated plants had emerged 186 DAT.

### *Statistical Analysis*

A linear regression model was used to determine if data from experiments A and B, A and C, or C and B could be combined. The model excluded any treatments that were not common to both experiments. The model included both the herbicide treatment and experiment group as explanatory variables. To determine if the experiment group had a significant influence on the outcome of the experiment, the interaction effect of treatment by experiment was examined. The combination of experiments A and B resulted in high p-values ($p > 0.05$) for the majority of variables, indicating the treatments resulted in the same effect regardless of experiment, and that data from experiments A and B could be combined. The combination of experiments A and C or B and C resulted in very small p-values ($p < 0.05$) for all variables, indicating that it was not appropriate to eliminate experiment as an explanatory variable and that it was appropriate to analyze experiment C separately from experiments A and B (which were combined). The reduced regression model was used for experiments A and B and experiment C using only treatment as an explanatory variable and 95% individual confidence intervals were calculated for the treatment means.

## Results and Discussion

### *Native Grass Establishment*

The 40 kg/ha seeding rate resulted in significantly higher grass seedling establishment (Table 1). Percent cover for the grass species was significantly higher at the 40 kg/ha seeding rate (42%) than at the 10 kg/ha (13%) 30 DAS. Mean grass density 45 DAS was also greater at the higher seeding rate (617 plants/m2 compared to 285 plants/m2). At 176 DAS mean grass density was measured as two fold greater in plots seeded with 40 kg/ha, but statistically equivalent to the mean grass density of subplots seeded at 10 kg/ha. The 40 kg/ha seeding rate resulted in a dense cover of grasses growing under the canopy of *F. japonica* and the desired initial outcome of the grass establishment experiment.

Throughout the 2008 growing season grass plants persisted in all experimental plots until the last observation (176 DAS). However, when native grass density was evaluated at the beginning of the second growing season (2009), one year after seedling, no grass plants were quantified within the experimental plots. When *F. japonica* leaf litter was brushed away from the soil surface of the plots, dead grass plants were visible. Although the grass plants did not survive winter conditions at this site, we documented that grasses could be established and survive initial competition with *F. japonica* and the foliar herbicide treatments applied to the *F. japonica*, some of which were non-selective (e.g. glyphosate). The winter after grass planting the experimental site did not experience typical seasonal flooding that would have removed the *F. japonica* leaf litter from the soil surface and thus the grass plants were most likely buried in a deep layer of leaf litter and physically unable to regrow the following spring. It is possible that in a riparian area that normally experiences at least some high water levels, established grasses might have a greater likelihood of survival. In this case, survival would depend on the *F. japonica* leaf litter being transported away during flood events and a grass rooting depth that allowed the plants to withstand flooding and scouring.

### *Herbicide Efficacy Field Studies*

Single herbicide applications at 11 DAT most treatment plots exhibited very little injury and additionally showed little signs of seasonal senescence (Table 2). Most of the mean percent injury ratings were equivalent to zero, the exception being the triclopyr treatment, which caused a mean percent injury of 35%. Other treatments were not statistically different than the control at 11 DAT. The triclopyr treatment also had a higher percent injury than other treatments 32 DAT (mean 77.5% injury). Following the 32 DAT rating the *F. japonica* were not rated again until the following growing season.

Percent injury to *F. japonica* was evaluated during the next growing season seven (Figs. 5a and 5b) and 12 months after treatment

(210 DAT and 378 DAT). Glyphosate and imazapyr resulted in the greatest injury symptoms 210 DAT (95% and 90% mean observed injury) (Table 2). The triclopyr treatment resulted in much less injury (63.8%), and the 2,4-D resulted in very little injury 210 DAT (20%). Final evaluation of percent injury was approximately one year after treatment (378 DAT). The 2,4-D treatment resulted in no injury and triclopyr treatment very little injury (22.5% mean observed injury) 378 DAT. Glyphosate resulted in 89.5% mean observed injury 378 DAT, and was equivalent to the imazapyr treatment which resulted in 81.3% mean observed injury.

Reduction in *F. japonica* biomass was evaluated by measuring new shoot density, height and diameter at approximately 25 cm aboveground 196 DAT (Table 3). None of the herbicide treatments had an effect on shoot diameter. The glyphosate, triclopyr, and imazapyr treatments had an equal effect on shoot density resulting in approximately three times lower new shoot density than control plots (85, 72, and 66 shoots/9 m2 compared to 248 shoots/9 m2). The mean height of the new shoots was 2-4 times shorter following the triclopyr and imazapyr treatments (24 cm and 13 cm tall) and was nearly 6 times shorter following the glyphosate treatment (10 cm tall) when compared to the control plants (57 cm tall).

### *Herbicide Tank Mixtures*

At 11 DAT the treated plots showed very little herbicide injury and additionally showed little signs of seasonal senescence (Table 4). Most of the percent injury ratings were equivalent to zero 11 DAT, the exception being the triclopyr/2,4-D treatment which resulted in 11% injury. The triclopyr/2,4-D treatment was equivalent to the imazapyr/aminopyralid treatment, and these treatments resulted in the highest mean percent injury 32 DAT (60% and 63.75%, respectively). The imazapyr/glyphosate treatment resulted in a lower mean percent injury (25%).

Reduction in *F. japonica* biomass was evaluated by measuring new shoot density, height and diameter at approximately 25 cm aboveground 196 DAT (Table 5). None of the tank mix herbicide treatments had an effect on mean shoot height at this rating time. All three treatments had an equal effect and caused a reduction in the shoot density

| Seeding rate | Mean % cover grasses 30 DAS | Mean nº grass seedlings/$m^2$ 45 DAS | Mean grass plants/ $m^2$ 176 DAS |
|---|---|---|---|
| **10 kg/ha** | 13.2 ± 0.9 b | 285 ± 50 b | 11 ± 3 a |
| **40 kg/ha** | 42.3 ± 3.5 a | 617 ± 86 a | 28 ± 19 a |

**Table 1.** Native grass percent cover 30 days after seeding (DAS) and grass density 45 and 176 DAS. Means (plus/minus the standard error of the means) within a column followed by the same lower-case letter are not significantly different ($p < 0.05$).

| Herbicide Treatment | Mean % injury | | | | Mean % leaf drop 32 DAT |
|---|---|---|---|---|---|
| | 11 DAT | 32 DAT | 210 DAT | 378 DAT | |
| **Control** | 0.0 b | 0.0 d | 0.0 d | 0.0 c | 75.0 ± 5.0 ab |
| **2,4-D** | 1.5 ± 0.6 b | 33.8 ± 5.5 b | 20.0 ± 4.1 c | 0.0 c | 45.0 ± 5.4 b |
| **Glyphosate** | 0.8 ± 0.8 b | 15.0 ± 8.4 bcd | 95.0 ± 0 a | 89.5 ± 0.5 a | 78.8 ± 6.3 ab |
| **Imazapyr** | 1.3 ± 0.8 b | 10.0 ± 2.0 c | 90.0 ± 2.0 a | 81.3 ± 4.3 a | 75.0 ± 2.4 a |
| **Triclopyr** | 35.0 ± 2.0 a | 77.5 ± 3.2 a | 63.8 ± 2.4 b | 22.5 ± 4.3 b | 76.3 ± 6.3 ab |

**Table 2**. *F. japonica* percent injury and percent leaf drop resulting from herbicide treatments applied on October 13, 2008, and quantified by visual rating 11, 32, 210, and 378 days after treatment (DAT). Means (plus/minus the standard error of the means) within a column followed by the same lower-case letter are not significantly different ($p < 0.05$).

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(mean density of treated plots was 3 -9 shoots in 0.75 m2 compared to 24 shoots in 0.75 m2 for the control). Mean shoot diameter at approximately 25 cm aboveground was slightly reduced by the imazapyr/aminopyralid treatment (0.3 cm) and the triclopyr/2,4-D treatment (0.8 cm), and shoot diameter was significantly reduced by the imazapyr/glyphosate treatment (0.1 cm) when compared to diameter of control plants (1.0 cm).

Percent injury to *F. japonica* was evaluated during the next growing season seven and 12 months after treatment (210 DAT and 378 DAT) (Table 4). The imazapyr/aminopyralid treatment resulted in the greatest injury symptoms 210 DAT. The imazapyr/ glyphosate treatment resulted in slightly less injury than the imazapyr/aminopyralid treatment, and the triclopyr/2,4-D treatment resulted in the least amount of injury 210 DAT. The final evaluation of percent injury was 378 DAT. The triclopyr/2,4-D treatment resulted in no injury symptoms 378 DAT. The imazapyr/glyphosate treatment caused 77.5% mean observed injury 378 DAT, and was equivalent to the imazapyr/aminopyralid treatment which resulted in a 57.5% mean observed injury rating.

| Herbicide treatment | Shoot density in 9 $m^2$ plot | Mean height (cm) | Mean diameter (cm) of stems at ~ 25 cm height |
|---|---|---|---|
| **Control** | 248 ± 21 a | 57 ± 4 a | 2.0 ± 0.4 a |
| **2,4-D** | 230 ± 18 a | 42 ± 2 a | 1.1 ± 0.0 a |
| **Glyphosate** | 85 ± 11 b | 10 ± 1 c | 0.6 ± 0.1 a |
| **Imazapyr** | 66 ± 9 b | 13 ± 3 bc | 1.2 ± 0.2 a |
| **Triclopyr** | 72 ± 11 b | 24 ± 2 b | 2.3 ± 0.2 a |

**Table 3.** Growth and biomass parameters of *F. japonica* 196 days after herbicide treatment (DAT). Means (plus/minus the standard error of the means) within a column followed by the same lower-case letter are not significantly different as indicated by 95% individual confidence intervals.

### *Aminocyclopyrachlor Efficacy Greenhouse Study*

Plants treated with aminocyclopyrachlor were the first to exhibit injury symptoms of all the greenhouse treated plants. Injury symptoms that resulted from treatment with aminocyclopyrachlor were similar to expected symptoms after treatment with a synthetic auxin herbicide (Group 4 herbicides). Within the first day after treatment plant stems began to curl or twist and leaves began to cup. Within one week new shoots were emerging from the rhizome and growing in a twisted manner. These symptoms continued to progress and after five weeks the tips of new shoots often swelled into a bulbous bud-like structure. White calluses also formed on shoot

| Herbicide treatment | Mean % injury | | | | Mean % leaf drop 32 DAT |
|---|---|---|---|---|---|
| | 11 DAT | 32 DAT | 210 DAT | 378 DAT | |
| **Control** | 0.0 b | 0.0 b | 0.0 c | 0.0 b | 46.8 ± 3.6 b |
| **Imazapyr/ Aminopyralid** | 0.3 ± 0.3 ab | 63.8 ± 3.8 a | 90.8 ± 2.7 a | 57.5 ± 13.6 a | 61.3 ± 2.7 ab |
| **Imazapyr/ Glyphosate** | 0.0 b | 25.0 ± 9.1 ab | 90.0 ± 5.1 ab | 77.5 ± 4.3 a | 85.0 ± 3.5 a |
| **Triclopyr/ 2,4-D** | 10.8 ± 3.3 a | 60.0 ± 4.6 a | 61.3 ± 3.1 b | 0.0 b | 90.0 ± 2.0 a |

**Table 4.** *F. japonica* percent injury and percent leaf drop resulting from tank mix herbicide treatments applied on October 13, 2008, and quantified by visual rating 11, 32, 210, and 378 days after treatment (DAT) Means (plus/minus the standard error of the means) within a column followed by the same lower-case letter are not significantly different ($p < 0.05$).

tips (Fig. 6). Necrotic tissue first appeared three weeks after treatment.

Aminocyclopyrachlor treatments resulted in greater injury than other active ingredients 7 and 21 DAT in the combined experiments A and B (Table 6). The level of injury was correlated to the rate of amino-cyclopyrachlor applied. The highest rate of amino-cyclopyrachlor resulted in the greatest injury of all treatments 63 DAT. The greatest amount of injury (78%) was caused by the 0.56 kg ai/ha treatment, which was equivalent to the amount of injury caused by the imazapyr treatment (76%). In the combined experiments A and B, the percent of control dry weight 70 DAT was not affected by amino-cyclopyrachlor applied at the 0.07 and 0.28 kg ai/ha rates, but was moderately reduced by the 0.035 kg ai/ha rate (Table 7). In experiment C, the greatest amount of injury (97%) was caused by the 0.56 kg ai/ha treatment (Table 8) and the percent of control dry weight 70 DAT was not affected by aminocyclopyrachlor applied at the 0.035, 0.07, 0.14, 0.28, 0.56 kg ai/ha rates (Table 9). However, at 186 DAT the 0.28 and 0.56 kg ai/ha rates aminocyclopyrachlor treatments had no regrowth after clipping.

Aminocyclopyrachlor appears to cause two physical responses that have contradictory effects on biomass and are correlated with rate. As the aminocyclopyrachlor rate increased the amount of leaf loss increased, causing a reduction in biomass. But as the rate increased the amount of new shoots and callus tissue also increased resulting in an overall increase in biomass in some cases. The observation of these contradictory effects may explain the lack of a true rate response in the measured biomass. The lack of *F. japonica* regrowth after treatment with amino-cyclopyrachlor indicates that while this active ingredient did not initially appear to be more effective than current standard herbicide treatments for *F. japonica* control in

| Herbicide treatment | Shoot density in 0.75 m$^2$ plot | Mean height (cm) | Mean diameter (cm) of stems at ~ 25cm |
|---|---|---|---|
| **Control** | 24.3 ± 2.6 a | 27.1 ± 2.6 a | 1.0 ± 0.1 a |
| **Imazapyr/ Aminopyralid** | 3.0 ± 1.7 b | 19.1 ± 4.0 a | 0.3 ± 0.3 ab |
| **Imazapyr/ Glyphosate** | 6.0 ± 1.8 b | 14.0 ± 2.2 a | 0.1 ± 0.1 b |
| **Triclopyr/ 2,4 -D** | 9.5 ± 1.3 b | 14.2 ± 1.8 a | 0.8 ± 0.3 ab |

**Table 5.** Growth and biomass parameters of *F. japonica* 196 days after herbicide tank mixture treatments (DAT). Means (plus/minus the standard error of the means) within a column followed by the same lower-case letter are not significantly different ($p < 0.05$).

| Herbicide | Rate | Average % injury 7 DAT | Average % injury 21 DAT | Average % injury 63 DAT |
|---|---|---|---|---|
| **Aminocyclopyrachlor** | 0.035 kg ai/ha | 13.3 ± 1.9 b | 23.9 ± 2.5 b | 21.7 ± 0.8 c |
| **Aminocyclopyrachlor** | 0.07 kg ai/ha | 17.0 ± 4.0 ab | 30.6 ± 4.8 ab | 45.0 ± 4.2 b |
| **Aminocyclopyrachlor** | 0.14 kg ai/ha | 23.6 ± 4.4 ab | 42.2 ± 3.7 a | 61.4 ± 4.6 b |
| **Aminocyclopyrachlor** | 0.28 kg ai/ha | 29.4 ± 5.0 a | 47.2 ± 4.9 a | 53.9 ± 5.6 b |
| **Aminocyclopyrachlor** | 0.56 kg ai/ha | 13.9 ± 1.6 b | 54.4 ± 1.3 a | 77.8 ± 2.1 a |
| **Imazapyr** | 0.84 kg ae/ha | 1.2 ± 0.6 c | 11.4 ± 1.9 c | 76.4 ± 2.2 a |
| **Glyphosate** | 3.37 kg ae/ha | 5.6 ± 1.6 bc | 19.2 ± 3.3 bc | 45.3 ± 4.3 b |
| **Control** | - | 0.0 c | 0.0 d | 0.0 d |

**Table 6.** *F. japonica* percent injury from herbicide treatments in combined greenhouse experiments A and B 7, 21, and 63 days after treatment (DAT). Means (plus/minus the standard error of the means) within a column followed by the same lower-case letter are not significantly different ($p < 0.05$).

terms of visual injury symptoms, it may be significantly more effective for controlling *F. japonica* regrowth than glyphosate and may have control comparable to that of imazapyr when used at the rates tested here. Other synthetic auxin (Group 4) herbicides have been shown to cause initial injury but over time are ineffective for *F. japonica* control. It is not known why aminocyclopyrachlor has a greater effect on *F. japonica* than other auxin-type herbicides but it is possible that it is due to the unique chemical structure of this new herbicide. It is also possible that this chemical has greater translocation into rhizomes and that metabolism of the chemical inside of plant cells is slow, resulting in long term shoot growth suppression.

## Conclusions

Timing of herbicide treatment and restoration planting needs to be

| Herbicide | Rate | Mean dry biomass as % of control | |
|---|---|---|---|
| | | 70 DAT | 186 DAT |
| **Aminocyclopyrachlor** | 0.035 kg ai/ha | 59.0 ± 3.5 ab | 18.8 ± 10.5 b |
| **Aminocyclopyrachlor** | 0.07 kg ai/ha | 107.9 ± 11.8 a | 1.6 ± 1.6 b |
| **Aminocyclopyrachlor** | 0.14 kg ai/ha | 75.5 ± 7.8 ab | 9.6 ± 9.6 b |
| **Aminocyclopyrachlor** | 0.28 kg ai/ha | 92.9 ± 12.2 a | 0.0 b |
| **Aminocyclopyrachlor** | 0.56 kg ai/ha | 48.3 ± 6.3 b | 0.0 b |
| **Imazapyr** | 0.84 kg ae/ha | 68.9 ± 8.9 ab | 0.0 b |
| **Glyphosate** | 3.37 kg ae/ha | 54.7 ± 7.0 ab | 6.1 ± 2.2 b |
| **Control** | - | 100 a | 100 a |

**Table 7.** *F. japonica* above ground biomass 70 DAT and above ground biomass of regrowth 186 DAT (after clipping) expressed as a percentage of control biomass in combined greenhouse experiments A and B. Means (plus/minus the standard error of the means) within a column followed by the same lower-case letter are not significantly different ($p < 0.05$).

| Herbicide | Rate | Ave. % injury 7 DAT | Ave. % injury 21 DAT | Ave. % injury 63 DAT |
|---|---|---|---|---|
| **Aminocyclopyrachlor** | 0.035 kg ai/ha | 22.2 ± 0.9 b | 23.9 ± 0.7 c | 35.6 ± 1.0 c |
| **Aminocyclopyrachlor** | 0.07 kg ai/ha | 22.8 ± 1.2 b | 27.2 ± 0.9 c | 38.9 ± 1.6 c |
| **Aminocyclopyrachlor** | 0.14 kg ai/ha | 23.9 ± 1.1 b | 27.2 ± 1.2 c | 33.3 ± 1.2 c |
| **Aminocyclopyrachlor** | 0.28 kg ai/ha | 25.6 ± 1.0 b | 30.0 ± 1.2 bc | 52.2 ± 6.5 c |
| **Aminocyclopyrachlor** | 0.56 kg ai/ha | 25.0 ± 1.2 b | 42.8 ± 4.9 b | 96.7 ± 2.2 a |
| **Imazapyr** | 0.84 kg ae/ha | 1.1 ± 0.5 c | 16.7 ± 9.2 bcd | 83.3 ± 2.4 b |
| **Glyphosate** | 3.37 kg ae/ha | 75.0 ± 1.7 a | 89.4 ± 1.5 a | 84.4 ± 1.8 b |
| **Control** | - | 0.0 c | 0.0 d | 0.0 d |

**Table 8.** *F. japonica* percent injury from herbicide treatments in greenhouse experiment C 7, 21, and 63 days after treatment(DAT). Means (plus/minus the standard error of the means) within a column followed by the same lower-case letter are not significantly different ($p < 0.05$).

| Herbicide | Rate | Mean dry biomass as % of control 70 DAT |
|---|---|---|
| **Aminocyclopyrachlor** | 0.035 kg ai/ha | 95.9 ± 5.8 a |
| **Aminocyclopyrachlor** | 0.07 kg ai/ha | 108.0 ± 8.0 a |
| **Aminocyclopyrachlor** | 0.14 kg ai/ha | 95.7 ± 6.0 a |
| **Aminocyclopyrachlor** | 0.28 kg ai/ha | 78.2 ± 9.1 a |
| **Aminocyclopyrachlor** | 0.56 kg ai/ha | 71.4 ± 3.1 b |
| **Imazapyr** | 0.84 kg ae/ha | 53.8 ± 5.7 b |
| **Glyphosate** | 3.37 kg ae/ha | 23.8 ± 3.9 c |
| **Control** | - | 100 a |

**Table 9.** *F. japonica* above ground biomass 70 DAT expressed as a percentage of control biomass in greenhouse experiment C. Means (plus/minus the standard error of the means) within a column followed by the same lower-case letter are not significantly different ($p < 0.05$).

adapted to the unique conditions at any *F. japonica* management site. Based on the results from this study, it does appear to be plausible, with some modification to our methods, to establish a native grass community at a *F. japonica* restoration site that can be used as a stepping stone community before proceeding to restoration with tree and shrub species. Further experiments designed to test both spring and fall grass seeding before and after herbicide application should be conducted in order to determine the most effective means of the integration of restoration with herbicide control of *F. japonica*.

We were able to establish a mixture of native grasses at a site with a dense *F. japonica* population by planting the grasses in early spring. The grasses grew through the summer but did not survive the winter conditions at the site. Though the causes of this failure are unknown, the successful establishment and growth during the summer period of active knotweed growth indicates potential for incorporation of restoration with grasses with targeted chemical control techniques. For future restoration planning, the spring planting date could be modified to suit the conditions at a site in a given year. Fall planting may also be feasible at some sites depending on environmental conditions and other factors including the dynamics of the water table or surface water. Testing the efficacy of grass seeding in the fall after herbicide treatment is needed. Beginning a restoration project with a fall herbicide treatment, then following with seeding grasses later that fall or the following spring after senescence and before *F. japonica* emergence, may be effective. Site preparation including dry biomass removal may need to be conducted prior to the grass seeding. The scenario used in this experiment (beginning with spring seeding followed by fall herbicide treatment) may have had more success if dry biomass had been removed from the site following autumn senescence.

Neither of the synthetic auxin herbicides (2,4-D and triclopyr) used alone in this study provided a satisfactory amount of *F. japonica* control. Imazapyr and glyphosate resulted in greatest level of control of the *F. japonica* of the four individual herbicides tested. However, these two products have very different costs of application. The aquatically-labeled glyphosate (Rodeo®, Aquamaster®) treatment has an approximate product cost of $160 US/ha and imazapyr (Habitat®) has an approximate cost of $302 US/ha (Ferrell & MacDonald 2008). Because the amount of injury to *F. japonica* evaluated a year after treatment was equal with these two products (81 to 89%) we conclude that the glyphosate was the most cost effective treatment evaluated in this experiment. The three tank mixtures utilized in this study also have very different product costs per hectare and cost significantly more than single product herbicide applications. The glyphosate/imazapyr mixture has an approximate product cost of $462 US/ha, the imazapyr/aminopyralid mixture $346 US/ha and the triclopyr/2,4-D mixture $555 US/ha. The imazapyr/aminopyralid tank mixture resulted in greatest amount of control (57.5%) 378 DAT. When land managers utilize an herbicide tank mixture for *F. japonica* control, these data suggest that imazapyr/aminopyralid would be the most appropriate choice of the three tank mixtures included in this experiment. But these results also suggest that glyphosate applied at 4.21 kg ae/ha is the most cost effective treatment option, and that tank mixtures of herbicides may not provide increased levels of control and may be cost prohibitive for land mangers in many cases.

The findings from our greenhouse chemical efficacy study indicate that aminocyclopyrachlor may have potential for *F. japonica* control in the field. Based on these data, it appears that the standard rate for *F. japonica* control would be approximately equivalent to the 4x rate used in these experiments (0.56 kg ai/ha). Applications rates in the range of 0.28 kg ai/ha to 0.56 kg/ha should be further examined under field conditions to determine a standard application rate of this product for *F. japonica* control.

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