Aquatic Uses of 2,4-D and Other Phenoxy Herbicides in the United States

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- 2,4-D is an inexpensive and effective option for controlling problematic aquatic weeds such as Eurasian watermilfoil.
- Before serious management programs were implemented there were over 500,000 acres of water hyacinth in just two states, Florida and Louisiana.
- Were 2,4-D unavailable, states would have to either increase their budgets for aquatic weed control by a factor of 13, or drastically reduce the acreage they treat.

Introduction

There have been many changes in aquatic plant management since the last version of this document was published. In the 1996 version of this publication, Dr. Carole Lembi, Purdue University Professor (now retired), provided strong evidence that the loss of 2,4-dichlorophenoxy acetic acid (2,4-D) for aquatic applications would result in a significant increase in the cost of aquatic plant management. That has not changed over the last 20 years. 2,4-D is still one of the most cost effective and selective methods to control invasive aquatic species like Eurasian watermilfoil (*Myriophyllum spicatum*) and variable leaf milfoil (*M. heterophyllum*). While 2,4-D is not the only herbicide option for water hyacinth (*Eichhornia crassipes*) control, it remains one of the two most cost-effective control strategies. It provides consistent control with less non-target impacts than glyphosate (Westerdahl and Getsinger 1988).

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Even with the introduction of a newer auxin herbicide, triclopyr, in 2002 and the introduction of other aquatic herbicides between 2002 and 2013, 2,4-D remains one of the most reliable and least expensive methods to control Eurasian watermilfoil (EWM), variable leaf milfoil, and water hyacinth (Netherland and Glomski 2008; Westerdahl and Getsinger 1988). Over the past 20 years, a great deal of research has focused on the non-target impacts of 2,4-D to better understand how to use this herbicide to control several key aquatic weeds with minimal impacts on the aquatic environment (Getsinger et al. 1982; Miller and Trout 1985; Wagner 2007; Wersal et al. 2010). Over the past two decades, 2,4-D rates have been reduced and this has been one factor contributing to the reduced cost.

At the same time that lake managers were fine tuning 2,4-D applications and looking more at whole lake applications with liquid 2,4-D at lower rates, two new issues emerged. The first is the potential for weed shifts. For example, the Tennessee Valley Authority (TVA) was battling a significant EWM problem until hydrilla (*Hydrilla verticillata*) was accidentally introduced in Lake Gunterville and other associated lakes in 2010. Over a period of approximately 3 years, the EWM was almost completely displaced by hydrilla, resulting in a significant decrease in the use of 2,4-D by the TVA. In 1996, the TVA was one of the few entities allowed to use liquid formulations of 2,4-D and was one the largest purchasers of 2,4-D for aquatic use in the US. In 2014, the TVA treated only 71.5 acres of EWM, primarily in Lake Guntersville, at a rate of 5 gal/acre (personal communication, David Webb, TVA Contractor). Between 1996 and 2014, there has been a 95% reduction the EWM infestation in TVA managed lakes.

The second issue and the one that is potentially more serious was the discovery of hybrid milfoil populations with reduced sensitivity to 2,4-D. These hybrids are crosses between the native northern milfoil (*M. sibericum*) and EWM (Moody and Les 2007). Applicators and lake managers, primarily in the upper midwest, began to realize that there were "difficult to control" milfoil populations. Based on genetic analyses, it was confirmed that these populations were hybrids between the native and invasive milfoil (La Rue et al. 2013). Examples with terrestrial weeds and one aquatic species (hydrilla) clearly demonstrate that selection pressure is the driving force behind resistance such that years of using 2,4-D to manage milfoil populations could result in the evolution of resistant populations. The other process at work in this situation is heterosis, or hybrid vigor. These hybrid milfoils grow faster than either parent and require significantly higher rates of 2,4-D for control; however, not all hybrid population show increased 2,4-D tolerance (Poovey et al. 2007). This is a topic of significant interest and may impact the long-term viability of 2,4-D as an aquatic herbicide for milfoil management. Increased awareness of hybrid milfoil populations has resulted in several companies providing DNA analysis to determine the extent of hybridization so that public and commercial applicators can plan for the most appropriate management strategy.

Costs and Benefits

For those working in the area of aquatic plant management as a business or as local, state, or federal water managers, the negative impacts of invasive or nuisance aquatic plants seems obvious, but to the general public, issues like reductions in native species diversity or reductions in ecosystem services mean very little. The general public is most likely to understand that these invasive aquatic plants negatively impact their recreational experience or the value of their lake front property.

Boating, fishing, and general tourism are extremely important to the economies of states like Vermont, New Hampshire, Wisconsin, Washington, Idaho, and Florida just to name a few. Boating alone is billion dollar a year business, supporting nearly a million jobs, 35,000 businesses, with spending on an annual basis of $83 billion (NMMA 2013). In 2006, according to the US Fish and Wildlife Service (USFWS) (2006), 24.4 million freshwater anglers took 337 million fishing trips, spending approximately $26.3 billion on fishing related expenses (food, lodging, travel, equipment). These popular recreational activities and their related businesses are highly dependent on access to waters of the US that are unencumbered by invasive aquatic plants.

The loss in property value ranged between 13% and 40% when lakes were infested with Eurasian watermilfoil (Johnson and Meder 2013; Halstead et al. 2003).

Several research studies in Wisconsin and New Hampshire clearly illustrate the negative impacts of invasive aquatic plants on the value of lake front property. The loss in property value ranged between 13% and 40% when lakes were infested with EWM (Johnson and Meder 2013; Halstead et al. 2003). These decreases in home values also significantly affected state and local tax revenue. In many of these states, smaller lakes are privately owned, so homeowner associations need to have some kind of self-assessment in order to generate the funds to aggressively manage aquatic weeds. This is another drain on the local economy. In Vermont, New Hampshire, Wisconsin, and Washington, the state does provide some grant funding in the form of cost sharing to help struggling lake associations deal with the issue of aquatic weeds (personal communications with Michelle Nault, Wisconsin Department of Natural Resources; Amy Smagula, New Hampshire Department of Environmental Services; Ann Bove, Vermont Department of Environmental Conservation; and Jon Jennings, Department of Ecology, State of Washington).

In many states, aquatic weed infestations are present in large public access lakes, reservoirs, and river systems that are managed by local, state, or federal agencies. The typical market driven economic analysis to determine the impact of invasive aquatic plants does not necessarily work in these situations because of the “public good” aspect of these aquatic resources (Rockwell 2003). Rockwell (2003), in a white paper written for the Aquatic Ecosystem Restoration Foundation, describes a methodology commonly used to do benefit/cost analysis in a “public good” situation. The cost is easily determined: a contractor/applicator treats so many acres with a herbicide at some fixed cost per acre or a contractor performs some kind of mechanical operation at some cost per acre. The difficulty comes with the benefit part of the equation. One common method for determining benefit is the “recreational benefit estimation” in which the person recreating is asked about their “willingness-to-pay” (WTP) for a service that is currently free. WTP is determined for a lake with invasive weeds that interfere with boating, fishing, and swimming and for a lake without aquatic weeds. Six published studies were compared that looked at lakes from British Columbia to Florida and the benefit/cost ratio (B/C ratio) ranged from 1:1 to 300:1, illustrating the difficulty in determining benefits of managing or preventing the introduction of invasive aquatic plants. Rockwell (2003) also suggests that there are very few published studies where the impact of aquatic weeds and the benefits of control have been sufficiently documented.

A recent publication from the Council for Agricultural Science and Technology (CAST), compiled a significant amount of publicly available information documenting the impact of terrestrial and aquatic invasive species, both plant and animal (Getsinger et al. 2014). The cost of all invasive species across the US was estimated to be $120 billion/year in damages and economic losses (Pimentel et al. 2005). A little more than 10%, or $14 billion/yr was associated with aquatic species (Pimentel 2005). For one of the important aquatic species controlled by 2,4-D, EWM, $400 million per year is the cost associated with managing a weed population that can no longer be controlled mechanically or is too widespread for eradication (Pimentel 2005)[1].

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Florida is one state with a very comprehensive management and reporting program. It has been battling invasive aquatic plants of every description for over 100 years. First it was water hyacinth in the early 1900s, later came hydrilla (1950s), and more recently local, state and federal land managers waged a very successful eradication program against the invasive tree species, melaleuca (*Melaleuca quinquenervia*). As a result of this long, documented struggle to preserve the uniqueness of Florida's aquatic ecosystems, it has by far the most comprehensive program in the country for dealing with aquatic plant management. Consequently, Florida is able to provide the most complete cost accounting.

In 2014, Florida spent approximately $14.3 million in both state and federal funds for aquatic plant management operation ($1.7 million in federal and $12.6 million state funding) (Schardt 2014) on weed management in public waterways and lakes. It is worth noting that these figures do not include funds spent by small lake associations or privatelandowners to manage aquatic weeds on private land. Thanks to continued state

[1] This figure was derived from several assumptions: 1) that the cost per acre is $800; and 2) that there are 490,000 acres treated each year, for a total of $400 million (Lembi 1996). Rockwell (2003) suggests that around $100 million is spent each year to control aquatic weeds, so it seems unlikely that the control of EWM accounts for most of the herbicide use. Using web searches to estimate the total number of EWM infested acres in the US, it is possible that there are 400,000 to 600,000 surface acres with some level of EWM infestation, but it seems unlikely that all of these are controlled and that the cost per surface acre is $800. The cost per surface acre could significantly vary depending on water depth and control strategy employed. This just another illustration of how difficult it is to piece together a comprehensive picture of even a single aquatic weed.

support since the 1990's, Florida has reduced hydrilla acres from a high of approximately 100,000 in 1994 to about 21,000 acres in 2014. After hitting a peak in 2002-2003, the total expenditures for hydrilla control have decreased by just over $12 million in the 2013-2014 season. Over a similar time period, the net benefit from aquatic plant management in 13 public lakes in Florida has been estimated at nearly $60 million/yr (Adams and Lee 2007).

Florida also has a long history with water hyacinth; one of the key weed species controlled by 2,4-D. At one time, water hyacinth covered about 125,000 acres of public waterways in Florida. There are still 250 public waterways with some level of infestation, but the vast majority of sites are less than 10 acres (Schardt 2015). It has taken nearly 35 years to reduce water hyacinth acres to a few thousand, but the current maintenance control program is critical to keeping management costs and environmental impacts at the lowest possible level. In 2014, 2,4-D ranked as the fourth most used aquatic herbicide in Florida, with approximately 14,000 lbs applied. About 1/3 of that total was being used for water hyacinth, while the rest was used to control other floating aquatic plants (Schardt 2015). Water hyacinth remains a very problematic aquatic invader across the southeastern US; Louisiana reports nearly 200,000 infested acres (Kravitz et al. 2004) (Figure 10.1).

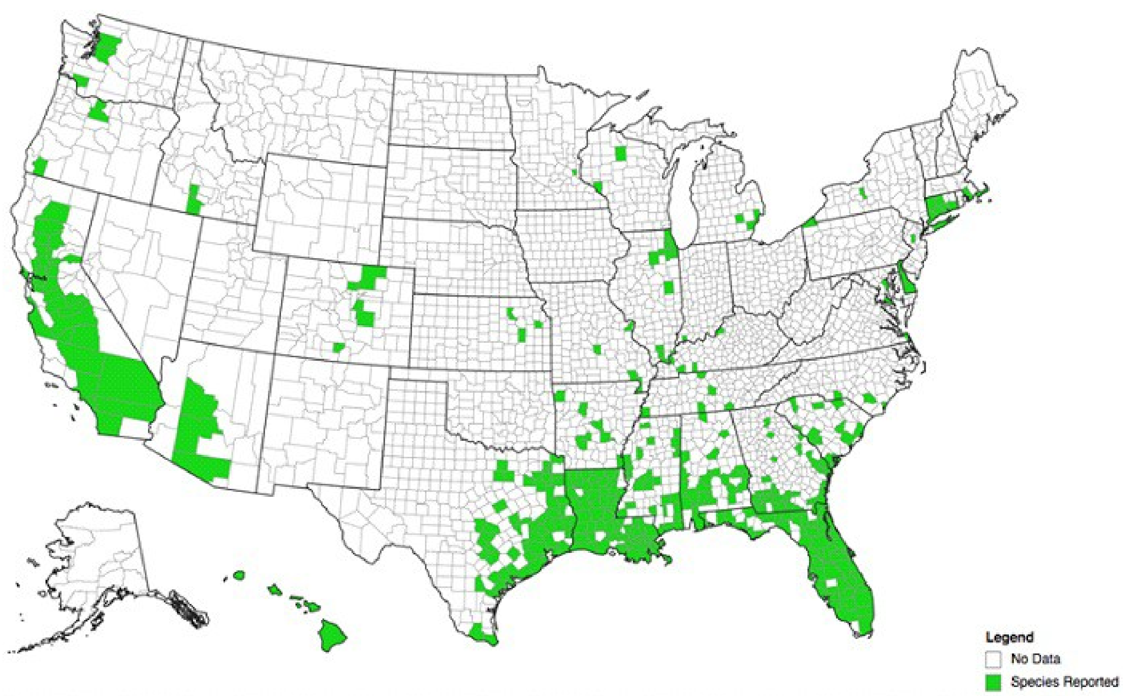

Figure 10.1. Water hyacinth (*Eichhornia crassipes*) distribution in USA (EDDMS 2015).

General Use Patterns of Auxin Herbicides in Aquatic Systems

As we pass the 70th anniversary of 2,4-D's commercialization in 1946, it is impressive that 2,4-D still has so many important uses and a minimal number of 2,4-D resistant weeds. In the US and Canada there are only 6 unique cases of weeds resistant to 2,4-D, which is remarkable considering that for some herbicide modes of action there are over 100 unique resistance cases (Heap 2015).

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In 1959, the first granular 2,4-D formulation was labeled for aquatic use. The butoxyethyl ester (BEE) 2,4-D was impregnated onto granules and the granules spread over the infested areas. This formulation permitted the extended release of 2,4-D BEE from the granules, which could then be rapidly absorbed by the target species. Once in the plant, the BEE would convert into the free acid of 2,4-D, since it is the free acid of 2,4-D that is toxic to plants. Depending on water chemistry and temperature, the 2,4-D BEE could also be converted to the free acid in the water column and then be absorbed by the plant.

This was the gold standard for EWM management for many years, and this strategy helped many lake managers deal with significant EWM infestations (Parsons 1998). Successful treatments often provided multiple years of EWM control; however, the registration of liquid amine formulations in 1976 did provide another management option. The use pattern changed somewhat with the introduction of liquid formulations.

After years of making directed, spot applications with the granular 2,4-D BEE formulations and noticing that, while the target concentration in the plant bed was intended to be 1-2 ppm 2,4-D, what eventually happened was a low dose treatment across the whole lake. One of the most comprehensive studies of this low dose, whole lake treatment concept was conducted in Northern Wisconsin (Nault et al. 2014). Two very similar lakes were treated with 2,4-D at concentration of 0.275 and 0.5 ppm, and while both treatments significantly reduced EWM frequency and biomass, the 0.5 ppm treated significantly impacted the native plant community. The 0.275 ppm treatment did not impact the native plant community and provided 90% reduction EWM for several years. This study identified one of the factors that has reduced the cost of 2,4-D treatments. 2,4-D degradation was significantly slower than anticipated, resulting in a lower 2,4-D concentration for a period that far exceeded the commonly recommended contact time of 12-48 hours. (see Figure 10.2 for general distribution of EWM in the US).

For over 45 years, 2,4-D was the only auxin herbicide labeled for aquatic use. In 2002, triclopyr was registered for aquatic use as the triethylamine salt. Previously, triclopyr was sold in two forms, the triethylamine (TEA) and BEE. These products were used primarily for woody plant and herbaceous perennial weed control in non-crop, industrial sites, rights-of-way, pipelines, railroads, and roadsides. Triclopyr BEE was often the herbicide of choice for basal bark treatments. Like most auxin herbicides, triclopyr is selective and controls many dicot species with little impact on monocot species. Triclopyr is also available as a granular formulation with an aquatic use pattern very similar to granular 2,4-D.

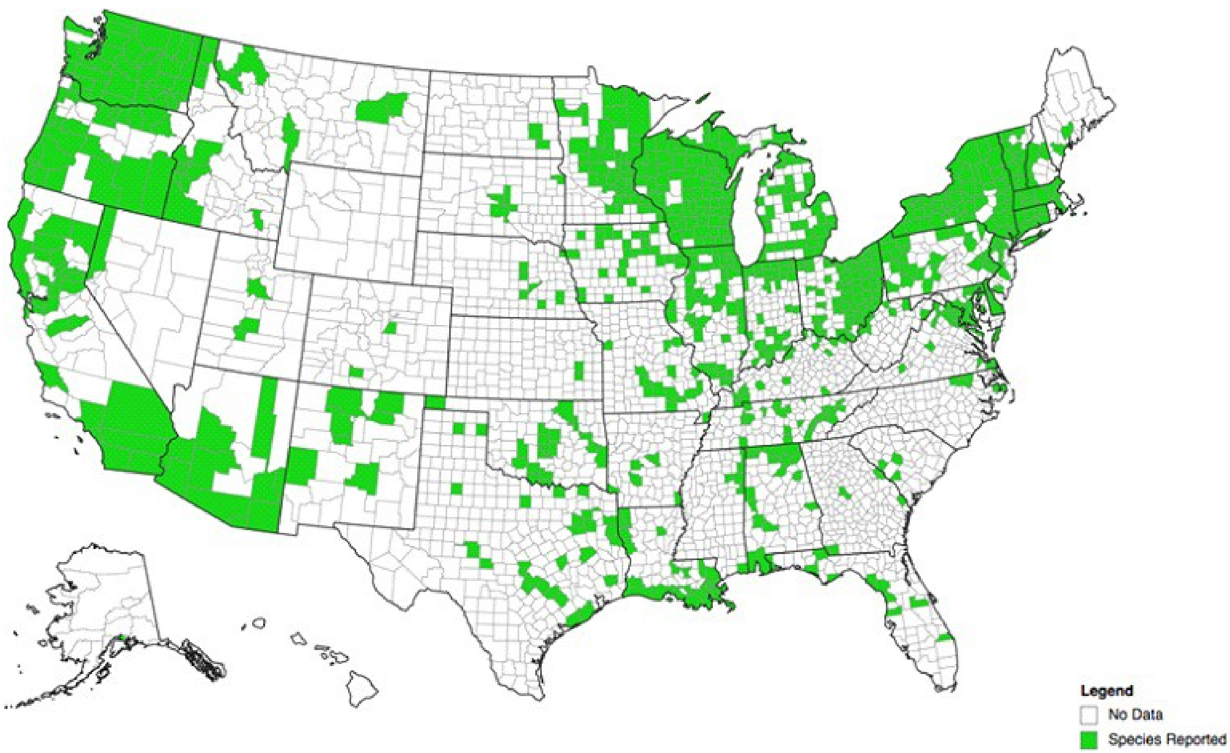

Figure 10.2. Eurasian watermilfoil (*Myriophyllum spicatum*) distribution by county in the USA (EDDMS 2015).

As previously mentioned, water hyacinth is the other major weed species where 2,4-D is a very important management option. Before serious management programs were implemented there were over 500,000 acres of water hyacinth in just two states, Florida and Louisiana. Water hyacinth has even become a problem weed in Sacramento River Delta (Angela Llaban, personal communication). For many years, 2,4-D was the primary herbicide used to control water hyacinth. Glyphosate did not receive an aquatic label until 1977, and since then water hyacinth control has been based on these two herbicides. 2,4-D works well to selectively control water hyacinth.

Variable leaf milfoil is another member of the milfoil family that has become a serious aquatic invader in the Northeast, especially in New Hampshire (Amy Smagula, personal communication). It is a Class A noxious weed in Vermont. Interestingly, it is a native species and listed as endangered in Ohio and Pennsylvania (USDA 2007). The water chemistry of New

Hampshire lakes appears to be very conducive to the establishment and growth of this aquatic plant. When growing in the slightly acidic, low alkalinity New Hampshire lakes, variable leaf milfoil is extremely aggressive. Netherland and Glomski (2008) confirmed what many lake managers and state officials had suspected: 2,4-D BEE was significantly more effective in controlling variable leaf milfoil than other aquatic herbicides. For a variety of factors, including water chemistry, 2,4-D BEE even outperformed 2,4-D amine and triclopyr, providing better control with shorter exposure times. Variable leaf milfoil is not as widespread as EWM or water hyacinth (see Figure 10.3), but is still invasive in some areas and 2,4-D BEE provides the best management option.

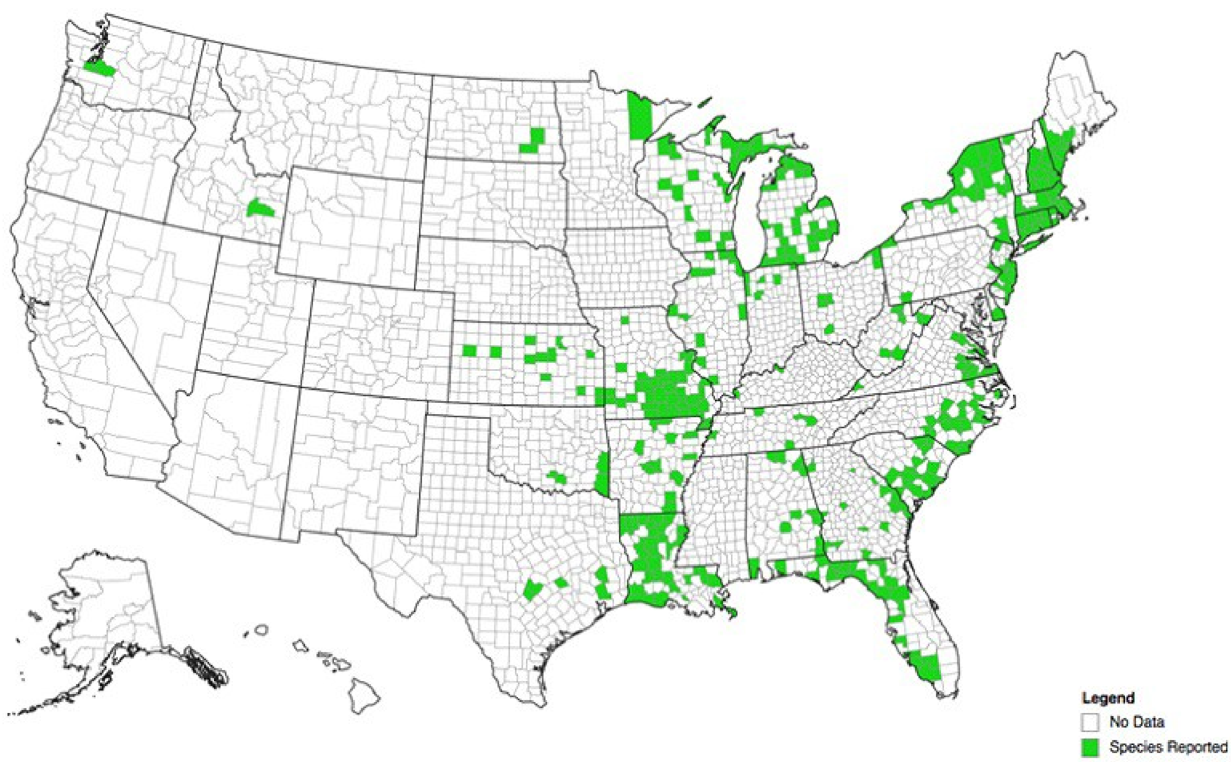

Figure 10.3. Variable leaf milfoil (*M. heterophyllum*) distribution in the USA by county (EDDMS 2015).

Alternative Herbicides and Other Management Strategies

The price for these three alternative herbicides is 19 to 146 times higher per pound of active ingredient than 2,4-D.

In 1996, there were really only two other herbicide options to control EWM: endothall and fluridone. Since then several other herbicides have been registered that have the potential to control EWM: imazamox, penoxsulam, and topramezone. To compare these herbicides to 2,4- D, a cost comparison was made using the amount of product needed to produce the necessary concentration in an acre foot (ac/ft) of water (Table 10.1). The necessary concentration was one that provided selective control under average conditions (low water exchange). An ac/ft of water is approximately 2.7 million pounds, so to establish an herbicide concentration of 1 ppm would require the addition of 2.7 lb of active ingredient. The selective concentrations for some of these alternative herbicides are very low. Use rates for fluridone, topramezone, and penoxsulam range from 0.01-0.09 ppm, significantly lower than 2,4-D. The cost for a pound of active ingredient is much higher for all herbicide alternatives. The price for these three alternative herbicides is 19 to 146 times higher per pound of active ingredient than 2,4-D. That is why even with significantly lower use rates, 2,4-D is still more cost effective.

There are two important parameters to consider with any aquatic herbicide used to control submersed aquatic weeds like EWM. As previously mentioned, herbicide concentration is one of these important parameters. The other part of the equation is contact or exposure time (Netherland 2014). The combination of these two parameters is known as concentration/exposure time or CET. In addition to the increased cost per pound of active ingredient, many of these herbicide alternatives have very long exposure times compared to 2,4-D. For example, fluridone, topramezone and penoxsulam all have exposure times greater than 45 days. This is a limitation that would require very minimal water exchange over that time period. For comparison, the exposure time for 2,4-D ranges from 12-48 hours, depending on concentration.

The only alternative herbicide with CETs similar to 2,4-D is endothall. Endothall was labeled for aquatic use in 1960 (Table 10.1) and has seen a significant increase in use over the past few years because it controls fluridone resistant hydrilla and is labeled for use in irrigation systems to control several pondweed species. Endothall is considered a contact herbicide, but does control EWM as a stand-alone product at rates of 1.5-2 ppm. The reason that endothall is not a direct replacement for 2,4-D is the cost per pound of active ingredient. The cost to treat an ac/ft of water is approximately 7 times greater with endothall than with 2,4-D.

The main target weed species for surface applications of 2,4-D is water hyacinth. Water hyacinth is still considered one of the world’s worst aquatic weeds, causing problems in all tropical and subtropical regions around the world (Barrett 1980). The distribution map in Figure 10.1 shows that water hyacinth’s distribution in the US is limited because the plant has very little cold tolerance; however, populations that occur in more northern latitudes could reappear each year from seed (Barrett 1980; Owens and Madsen 1995; Adebayo et al. 2011).

Table 10.1. Use pattern and cost associated with aquatic herbicides used to control Eurasian watermilfoil (*Myriophyllum spicatum*).

Active Ingredient (Registration yr)	Trade Names[a]	Form of Parent Compound[b]	Comment	Use Rate prod/ac ft (conc. ppm)	Cost[c] ($/ac ft)
2,4-D liquid (1976)	Hardball® Alligare 2,4-D amine® Clean Amine® Weedar 64® Weedestroy AM 40®	acid DMA DMA	Under average conditions 0.5-1 ppm should provide control. Under difficult conditions rates of 1-2 ppm might be necessary, but could impact some desirable species	25-90 oz (0.5-2 ppm)	$4.50-18
2,4-D granular (1959)	Sculpin® Navigate®	DEA BEE	Granular treatments are preferred in many areas, used for spot treatments; BEE provides excellent control of variable leaf milfoil	28.4-56.8 lb (2-4 ppm)	$85-190
Triclopyr liquid (2002)	Navitrol® Renovate 3® Alligare Triclopyr®	TEA	Second auxinic herbicide with many of the use patterns of liquid 2,4-D; Provides the same selectivity as 2,4-	0.7-2.3 gal (0.75-2.5 ppm)	$69-170
Triclopyr granular (2002)	Renovate OTF® Navitrol DPF®	TEA	Similar to granular 2,4-D BEE in use pattern and selectivity	27-54 lbs (1-2 ppm)	$128-256
Endothall (1960)	Aquathol K®	K^+ salt	Similar contact time to auxin herbicides, used at lower rates in combination with auxin herbicides to control hybrid milfoil	0.9-1.3 gallons (1.5-2 ppm)	$60-87
Fluridone (1986)	Sonar AS®	non-ionizable	Fluridone requires extended contact times and may need follow up applications	1- 7.7 oz (0.01-0.09 ppm)	$14-114
Imazamox (2008)	ClearCast® 2.7 G®	acid	Acetolactate synthase (ALS) inhibiting herbicide with low use rate and good selectivity	69 oz (0.2 ppm)	$131
Penoxsulam (2007)	Galleon®	non-ionizable	ALS inhibiting herbicide similar use pattern to imazamox	4.4-13.1 oz (0.025-0.075 ppm)	$71-213
Topramezone (2013)	Oasis®	acid	Inhibits the production of carotenoid pigments by inhibiting 4-hydroxyphenyl-pyruvate dioxygenase (4-HPPD)	3.7-6.2 oz (0.03-0.05 ppm)	$72-120

[a] not all registered trade names are listed, other products may be available

[b] abbreviations - DMA, dimethyl amine; BEE, butoxyethyl ester; TEA, triethyl amine; K^+ salt, potassium salt

[c] cost is for chemical only, does not include application costs

> *There are seven alternatives herbicides labeled for water hyacinth control that vary in cost between $13-$312 per surface acre. Glyphosate is comparable in cost to 2,4-D, while the other herbicide alternatives are 2 to 23 times more expensive than 2,4-D.*

There are seven alternative herbicides labeled for water hyacinth control that vary in cost between $13-$312 per surface acre (Table 10.2). Glyphosate is comparable in cost to 2,4-D, while the other herbicide alternatives are 2 to 23 times more expensive than 2,4-D. Glyphosate was not really that cost competitive with 2,4-D in 1996; however, over the past 20 years the cost of glyphosate has decreased significantly and in 2015, glyphosate and 2,4- D are comparable in price. The problem with herbicides like glyphosate and imazapyr is that they lack selectivity and will impact non-target plants. The main advantage of 2,4-D for control of water hyacinth is that it is highly effective and provides selective control. In California, 2,4-D is also considered very effective on South American sponge plant (*Limnobium laevigatum*). This is a relatively new aquatic invader found in the San Joaquin River and Sacramento-San Joaquin Delta.

Mechanical and biological controls have a place in aquatic plant management. For 2,4-D's two most commonly targeted species, EWM and water hyacinth, there are very few biological control options. There is evidence that the native milfoil weevil (*Euhrychiopsis lecontei*) prefers the invasive milfoil over the native northern milfoil (Solarz and Newman 1996) and attempts have been made to do augmentative biological control using this insect. Unfortunately, results are completely unpredictable (Newman 2008) and with a cost of $1 per weevil this management option is very expensive (Hoffman 2011). There have been three insects successfully established for water hyacinth control, two weevils (*Neochetina dichhorniae* and *N. buchi*) and one moth (*Niphograpta albiguttalis*). These insects were released in the 1970s and while they appear to have impacts on biomass and flower productions, other control methods are required to maintain water hyacinth populations at acceptable levels (Southeast Exotic Plant Pest Council 2015). A fourth biocontrol agent from Argentina, *Megamelus scutellaris*, has shown promising results and is being mass-reared for redistribution (Tipping 2015).

Mechanical harvesters are very expensive to operate and in many cases only make the problem worse by cutting plants into small pieces that float off and establish new infestations. The rapid growth rates of many aquatic species means that mechanical harvesters have a difficult time just keeping up with the ever increasing plant biomass which must be offloaded from the harvester and trucked to a dump site. Mechanical control is rarely a good alternative to proper herbicide applications.

Table 10.2. Use pattern and cost associated with aquatic herbicides used to control water hyacinth (*Eichhornia crassipes*).

Active Ingredient	Trade Names[a]	Formulation[b]	Comment	Use Rate (prod/ac)	Cost[c] ($/surface ac)
2,4-D (1976)	Hardball® Alligare 2,4-D amine® Clean Amine® Weedar 64® Weedestroy AM 40®	acid amine amine	Selective herbicide with systemic activity; Requires spray adjuvant that is approved for aquatic use; South American sponge plant control in addition to water hyacinth.	1 gal	$13
Triclopyr (2002)	Navitrol® Garlon 3A® Renovate 3A® Triclopyr 3SL®	TEA	Another systemic auxin herbicide similar in use pattern to 2,4-D; Requires an approved aquatic adjuvant to achieve control	2-8 qts	$37-148
Glyphosate (1977)	Rodeo® AlligarePRO® AquaNeat® Shore-Klear®	IPA	Non-selective, controls a number of floating aquatic species; Requires approved adjuvant	2-3 qts	$13-19
Diquat (1962)	Reward® Harvester® Littora®	Br^+ cation	Non-selective, contact herbicide that requires complete covered and potentially multiple applications to be effective	0.5-2 gal	$46-184
Imazapyr (2003)	Habitat® Polaris® Ecomazapyr®	acid	Systemic but non-selective at the rates required to control water hyacinth; Similar mode of action to penoxsulam and bispyribac	32 oz	$22
Penoxsulam (2007)	Galleon®	non-ionizable	An aquatic approved surfactant must be used with all foliar applications; Does have both foliar and in-water activity	2-5.6 oz	$32-91
Bispyribac-sodium (2012)	Tradewind®	acid	Needs approved surfactant, can be absorbed by both roots and leaves, best when applied to smaller plants	1-2 oz	$40-80
Topramezone (2013)	Oasis®	acid	Requires an approved surfactant for foliar application and maximum coverage, also has in water activity; new mode of action for aquatics	4-16 oz	$78-312

[a] not all registered trade names are listed, other products may be available

[b] abbreviations; - MA, dimethyl amine; BEE, butoxyethyl ester; TEA, triethyl amine; IPA, isopropylamine; Br^+ salt, bromine salt

[c] cost is for chemical only, does not include application costs

Even though 2,4-D is the most cost effective management option in many situations, there are times when other options should be considered. There are several restrictions on the aquatic use of 2,4-D that could determine if it is the most appropriate strategy. The 2,4-D concentration must be below 0.1 ppm in order to use treated water for irrigation. There are also setbacks from potable water intakes and requirements that water samples be analyzed to ensure that 2,4-D concentrations are below the drinking water maximum contaminant level (MCL) of 0.07 ppm. It is possible that under certain circumstances where these conditions cannot be met that one of the herbicide alternatives shown in Tables 10.1 and 10.2 might be a better option.

Potential Loss of 2,4-D

The cost comparisons listed in Table 10.1 make it evident that the loss of 2,4-D for control of submersed aquatic species would result in a massive increase in the cost of chemical control operations. Even with another auxinic herbicide (triclopyr) now available, the cost differential between 2,4-D and triclopyr is significant. With stagnant state and federal budgets, this would have a significant impact on the number of ac/ft that could be treated. There are two ways to respond to any de-registration of 2,4-D for aquatic use. The first would be to simply determine the number of ac/ft treated in a particular state, calculate the difference between the next least expensive alternative herbicide, and come up with an increased cost. This approach assumes that state budgets could accommodate the increased expense. The more likely outcome would be that budgets will remain unchanged, and the number of ac/ft treated would be drastically reduced. Significant reductions in acres managed means that infested acres will continue to increase. The only option for many states would be to contain the number of water bodies infested by vigorous boat inspection programs and educational/awareness programs with volunteers providing the outreach and monitoring.

Without 2,4-D state budgets for Eurasian watermilfoil management would need to increase 13 times; or more likely the number of ac/ft treated would be reduced by 92%.

Taking the midpoint concentration for 2,4-D (1 ppm = $9/ac ft) and the average cost of the other alternative herbicides (average cost of midpoint concentration = $119/ac ft), the increased cost or decreased ac/ft treated would be a factor of approximately 13. State budgets for EWM management would need to increase 13 times; or more likely the number of ac/ft treated would be reduced by 92%, assuming the same level of state or federal funding. For many of the privately owned lakes managed by lake associations, the impact of losing 2,4-D would be devastating. The costs associated with other products would make it extremely difficult for owners of lakefront properties to recover lost property value. These losses in property value can be substantial. In Washington state, Oden and Tamayo (2014) estimated a 19% decline in property value when lakes were infested with EWM. With an average home price around $500,000, that equates to a $94,385 reduction in a property's sale price.

For water hyacinth management, the main issue with the loss of 2,4-D would be the lack of selectivity among the most cost comparable alternatives. Glyphosate is comparable in price to 2,4-D, but as previously mentioned, lacks selectivity. Imazapyr has the same issue with lack of selectivity and is about twice the price of 2,4-D. Triclopyr, which would provide similar selectivity to 2,4-D, is about 3 times the cost per surface acre. The more recently registered aquatic herbicides, penoxsulam, bispyribac-sodium, and topramazone, are 3 to 6 times more expensive per surface acre. As such, the loss of 2,4-D for water hyacinth control would be costly in terms of dollars and environmental impacts.

2,4-D Resistant Aquatic Weeds

In 1996 there were no examples of 2,4-D resistant aquatic weeds, or aquatic weeds that were resistant to any herbicides. The selective pressure was not as intense in aquatic environments compared to terrestrial environments, and there were very few examples of aquatic weeds being exposed to large scale selection events on a regular basis.

The one aquatic weed that did fit that general scenario is hydrilla. In Florida, the hydrilla infestation peaked in the mid 1990's at about 100,000 acres (Schardt 2015) and was being treated on a regular basis with fluridone. By 2000, aquatic plant managers were concerned about the lack of control with some large-scale fluridone treatments. It had taken years of evolution to select for resistant individuals, and now the resistance is very widespread.

The story of hydrilla resistance to fluridone should be a wake-up call that herbicide resistance is an issue that needs to be considered anytime a large plant population is exposed to a high level of selection pressure over multiple years. The evolution of herbicide resistance occurs in terrestrial and aquatic plants. Since 2,4- D is such an important tool for EWM management, it is important to maintain 2,4-D's efficacy. Unfortunately, it was recently reported that some hybrids between EWM and northern milfoil have a decreased sensitivity to 2,4-D, and at the same time are more aggressive invaders than either parent (La Rue et al. 2013). The contribution that heterosis or hybrid vigor makes to invasiveness is well documented (Schierenbeck and Ellstrand 2009); however, in this case not all hybrids have reduced 2,4-D sensitivity (Poovey et al. 2007), but all populations that show reduced 2,4-D sensitivity are hybrids (La Rue et al. 2013). Concerns about managing these hybrid milfoil populations were universal for interviewees (see the list people consulted) from the upper mid-west and northeast states. The current management strategy for controlling these hybrid milfoil populations is to combine 2,4-D with endothall, or to use fluridone, or triclopyr. As previously mentioned, endothall has CET requirements similar to 2,4-D, so by combining two herbicides, these hybrid populations are being managed (J. G. Skogerboe, personal communications). Two things could have contributed to the evolution of reduced 2,4-D sensitivity in these hybrid milfoil populations: (1) using the same herbicide for multiple years and (2) using low dose treatments. Lagator et al. (2013) demonstrated with *Chlamydomonas reinhardtii* as a model organism that the best way to slow the evolution of herbicide resistance was to use herbicide mixtures at high doses. By using low doses of the same herbicide, herbicide resistance is more likely to develop. These findings have significant implications for all aquatic plant managers.

Conclusion

Even though 2,4-D has been used for aquatic plant management in the granular form since 1959 and in liquid form since 1976, there is only one potential case of an herbicide resistance aquatic species (using the Weed Science Society of America definition for resistance). Unfortunately, this case involves one of the most important aquatic weeds controlled by 2,4-D - EWM. EWM can be managed at a lower cost with liquid 2,4-D than with any other herbicide approved for aquatic use (Table 10.1). The granular formulations for 2,4-D can also be cost effective, but that is harder to calculate since these formulations are often used for high dose, spot treatments. A second auxinic herbicide was made available in 2002, but has not replaced 2,4-D for management of either EWM or water hyacinth. Individuals interviewed in the preparation of this manuscript were universally in favor of maintaining 2,4-D as a management option for both EWM and water hyacinth management. While 2,4-D is not suited for all situations due to irrigation and drinking water restrictions, it remains a viable management tool even after 59 years of aquatic use.

While 2,4-D is not suited for all situations due to irrigation and drinking water restrictions, it is still a viable management tool even after 59 years of aquatic use.

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