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Improvements in the Use of Aquatic Herbicides and Establishment of Future Research Directions

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ABSTRACT

Peer-reviewed literature over the past 20 years identifies significant changes and improvements in chemical control strategies used to manage nuisance submersed vegetation. The invasive exotic plants hydrilla (*Hydrilla verticillata* L.f. Royle) and Eurasian watermilfoil (*Myriophyllum spicatum* L.) continue to spread and remain the plant species of greatest concern for aquatic resource managers at the national scale. Emerging exotic weeds of regional concern such as egeria (*Egeria densa* Planch.), curlyleaf pondweed (*Potamogeton crispus* L.), and hygrophila (*Hygrophila polysperma* (Roxb.) T. Anders), as well as native plants such as variable watermilfoil (*Myriophyllum heterophyllum* Michx), and cabomba (*Cabomba caroliniana* Gray) are invasive outside their home ranges. In addition, there is always the threat of new plant introductions such as African elodea (*Lagarosiphon major* (Ridley) Moss) or narrow-leaf anacharis (*Egeria najas* Planchon). The registration of the bleaching herbicide fluridone in the mid 1980s for whole-lake and large-scale management stimulated numerous lines of research involving reduction of use rates, plant selectivity, residue monitoring, and impacts on fisheries. In addition to numerous advances, the specificity of fluridone for a single plant enzyme led to the first documented case of herbicide resistance in aquatic plant management. The resistance of hydrilla to fluridone has stimulated a renewed interest by industry and others in the registration of alternative modes of action for aquatic use. These newer chemistries tend to be enzyme-specific compounds with favorable non-target toxicity

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profiles. Registration efforts have been facilitated by increased cooperation between key federal government agencies that have aquatic weed control and research responsibilities, and regulators within the U.S. Environmental Protection Agency (USEPA). We reviewed past and current research efforts to identify areas in need of further investigation and to establish priorities for future research directions in chemical management of submersed plants. The priorities we identified include: (A) improving methods for evaluating non-target impacts of herbicides with an emphasis on threatened and endangered species, or species of special concern; (B) improving herbicide performance in flowing-water environments, including irrigation canals; (C) screening and developing new herbicides to supplement fluridone for large-scale or whole-lake management approaches; (D) screening and developing new organic algaecides to supplement the use of copper-based compounds; (E) developing risk assessment tools to educate the public on the risks of invasive species and chemical management options; (F) increasing cooperative research with ecologists and fisheries scientists to evaluate the long-term impacts of invasive species introductions and herbicide programs on native plant assemblages, water quality, and fish populations; and (G) improving the integration of chemical control technology with other aquatic plant management disciplines. While circumstances may dictate setting new priorities or dropping current ones, the list we have generated represents our vision of the needs that will require the greatest focus over the next several years.

Key words: chemical control, invasive aquatic weed, submersed aquatic vegetation.

INTRODUCTION

Herbicides have been key tools in aquatic plant management, and they continue to play a major role in controlling nuisance aquatic vegetation in waters of the United States (Gallagher and Haller 1990, Netherland et al. 2005a). In the past 20 years, the use patterns of aquatic herbicides have evolved due to the registration of new products, the development of new application techniques and reduced use rates, and greater demand for selective control of invasive non-indigenous species. During this time, there has also been renewed emphasis on the potential toxicity of aquatic herbicides to non-target organisms as well as increased interaction with regulatory and resource management agencies.

Products have progressed from broad-spectrum inorganic compounds such as sodium arsenite (1900-1930s) and copper (1900s and still in wide use for algae control) to organic compounds such as 2,4-D, diquat and endothall that have been available for many decades, but are still valuable tools for aquatic plant control today (Table 1).[5] By the 1980s and 1990s, plant specific enzyme inhibitors, such as fluridone and glyphosate, with high toxicity to non-target organisms, were being used at relatively low doses (Netherland et al. 2005a). Included in this group were a collection of acetolactate synthase (ALS) inhibitors such as sulfometuron, bensulfuron-methyl, imazapyr, imazamox, penoxsulam, and byispyribac-sodium. Sulfometuron and imazapyr were evaluated in small-scale trials by Anderson and Dechoretz (1985). Bensulfuron-methyl was the first ALS inhibitor to be widely evaluated for aquatics and then field-tested from 1989-1991 under a USEPA Section 5 experimental use permit (EUP); Anderson and Dechoretz 1988, Langeland and LaRoche 1992, Langeland 1993, Getsinger et al. 1994a, 1994b, Langeland and LaRoche 1994, Van and Vandiver 1994). The mode of action of these enzyme-specific herbicides resulted in the opportunity for large-scale–whole-lake management (i.e., fluridone) with negligible risks to water quality. The use of herbicides in aquatic systems continues to provide cost-effective, site-specific, relatively long-term, and often selective control of many of the most troublesome invasive aquatic weeds, particularly the submersed species Eurasian watermilfoil (*Myriophyllum spicatum* L.), hydrilla (*Hydrilla verticillata* L.f. Royle), curlyleaf pondweed (*Potamogeton crispus* L.), and egeria (*Egeria densa* Planch.).

Although submersed plant and algae control are often viewed as distinct disciplines, aquatic resource managers must often treat for both problems, and many of the same environmental factors impact efficacy and treatment strategies. Copper-based compounds have dominated the algae control arena for many years due to consistent cost-effective performance and the lack of water use restrictions on drinking, swimming, or fishing, when used according to labels. This heavy reliance on a single tool has limited the interest and support of research to develop non-copper alternatives for algae control. Research shows that copper formulations, water quality, and algal density can impact treatment efficacy (Murray-Gulde et al. 2002). There is also recent evidence that copper-tolerant strains of algae are increasing in response to management (Lembi 2000). The emergence of, and publicity surrounding, harmful algal blooms (HAB) and their potential for release of toxins into the environment has stimulated significant interest in developing new management practices. One novel approach proposed for HAB management is to evaluate organic compounds with species-selective properties (Schrader and Harrier 2001, Schrader 2005). As freshwater resources continue to increase in functional, aesthetic, and economic value, development of cost-effective and environmentally sound strategies to target harmful or nuisance algae will become increasingly important.

We reviewed the major research and development (R&D) activities since the 1980s that have led to improved use of aquatic herbicides to control invasive weeds in public water bodies. In addition, we considered the key knowledge gaps that must be filled to continue the responsible use of aquatic herbicides and algaecides and developed a list of future directions to help guide R&D efforts.

RESEARCH EFFORTS DURING THE LAST TWO DECADES

Treating emergent plants (i.e., foliage above the water surface) with herbicides is a very straightforward process, similar to weed control in terrestrial environments where the herbicide is applied directly to the foliage. If the product is delivered to the foliage above the water line at the proper application rate and growth stage of the target plant and is not

[5]Chemical names for all products used in this article are provided in Table 1.

TABLE 1. A LIST OF REGISTERED AQUATIC HERBICIDES REVIEWED IN THIS ARTICLE, AND USES FOR THOSE CHEMICALS TO CONTROL SUBMERSED PLANTS.

Compound	Aquatic registration	Submersed use for aquatics	Comments	Chemical name
SECTION 3 LABELS				
Copper Copper chelates	1950s	Yes	Major use for algae control, but also used in combination with aquatic herbicides.	Not applicable
2,4-D	1959 (ester) 1976 (amine)	Yes	Systemic for submersed dicots such as Eurasian watermilfoil.	2,4-dichlorophenoxy acetic acid
Endothall	1960	Yes	Contact herbicide. Alternative to fluridone for resistant hydrilla.	7-oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid
Diquat	1962	Yes	Contact herbicide.	6,7-dihydrodipyrido[1,2-a:2',1'-c]pyrazinedi-ium ion
Glyphosate	1977	No	Emergent activity only.	*N*(phosphonomethyl)glycine
Fluridone	1986	Yes	Large-scale or whole-lake management.	1-methyl-3-phenyl-5-[-3(trifluoromethyl)phenyl]-4(1H)-pyridinone
Triclopyr	2002	Yes	Systemic for submersed dicots.	[(3,5,6-trichloro-2pyridinyl)oxy]acetic acid
Imazapyr	2003	No	Emergent use only.	(±)-2-[3,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-Imidazol-2-yl]-3-pyridinecarboxylic acid
Carfentrazone-ethyl	2004	Yes	Contact herbicide for dicots. Rapid contact activity.	α, 2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoate
Penoxsulam	2007	Yes	Large-scale or whole-lake management.	2-(2,2-difluoroehtoxy)-N-(5,8-dimethoxy[1,2,4]triazolo[1,5c]pyrimidin-2-yl)-6-(trifluoromethyl)benzenesulfonamide)
Imazamox	2008	Yes	Submersed use similar to fluridone and emergent use similar to imazapyr	2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid
OTHER AQUATIC PRODUCTS/REGISTRATIONS				
Sulfmeturon	Not applicable	Yes	Small-scale evaluations.	methyl 2-[[[[(4,6-dimehtyl-2-pyrimidinyl)amino)carbonyl]amino]sulfonyl]benzoate
Bensulfuron-methyl	1989-1991	Yes	Experimental Use Permit. Use pattern similar to fluridone.	methyl 2-[[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]-carbonyl]amino]sulfonyl]methyl]benzoate
Metsulfuron-methyl	2004	No	Section 24c FL. Emergent use only.	methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]methyl]benzoate
Bispyribac-sodium	2006	Yes	Under Experimental Use Permit. Use pattern similar to fluridone.	2,6-bis[(4,6-dimethoxy-pyrimidin-2-yl)oxy]benzoic acid
Flumioxazin	2006	Yes	Under Experimental Use Permit. Rapid contact activity.	2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propymyl)-2H-1,4-b benzoxazin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione
Quinclorac	2007	Yes	Uner Experimental Use Permit	3,7-dichloro-8-quinolinecarboxylic acid

washed away too quickly by a rainfall event, desired efficacy is achieved. In contrast, submersed plants are more difficult to control because the herbicide application is made to the water column and is subject to a variety of water exchange processes that can move the product off target or dilute the concentration, shortening the contact time required to achieve adequate control. Therefore, much of the research efforts over the past two decades have focused on chemical applications to the more complex situation of controlling weeds growing underwater.

While numerous technical advances have been made during this period, five key events in R & D have shaped the current patterns of aquatic herbicide use for submersed plants. The technological changes that occurred as a result of these events were based upon, and supported by, robust applied research programs. These events were:

1. the registration of fluridone and discovery that low use rates over extended exposures were key to providing target plant control
3. whole-lake management using herbicides and real-time residue monitoring to adjust treatment rates to target invasive species
4. the move to species-selective control through herbicide choice or through adjusting use rates or timing of application
5. development of herbicide resistance in hydrilla

6. routine interaction with the USEPA and other regulatory and resource agencies to facilitate understanding of regulatory and management issues.

Registration of the Herbicide Fluridone

Fluridone was the only herbicide that received a USEPA Section 3 (nation-wide) aquatic registration in the 1980s and was the first to be registered for submersed plant control since the early 1960s. With its site-specific mechanism of action on phytoene desaturase (PDS) inhibition, comparatively long residence time in the water column, and long period of time required for plant death, fluridone was unique in the suite of herbicides available for controlling submersed plants (Schmitz 1986). These characteristics caused many early operational failures, highlighting the need for an improved understanding of fluridone concentration and exposure time (CET) relationships to obtain consistently effective use in the field (Netherland et al. 1993, Netherland and Getsinger 1995a, 1995b). Once the extremely effective low dose CET relationship for fluridone was discovered (5 to 15 µg L^{-1} [parts per billion]) and long exposure of 60 to 120 days), the concept of treating large blocks of weeds (hundreds of hectares in size), to entire weed-infested lakes (thousands of hectares in size) and some slow flowing waters, became possible and economical (Fox et al. 1991, 1994, 1996, Smith and Pullman 1997, Getsinger et al. 2002, Madsen et al. 2002). While these extensive treatments changed the scale of aquatic plant management, the favorable nontarget toxicity profile and slow plant death mitigated many concerns regarding widespread direct impacts to fish and wildlife and dramatic changes in water quality (McCowen et al. 1979, Hamelink et al. 1986). The increased use of fluridone for whole-lake management did stimulate debate regarding the potential for significant loss of vegetation and plant community diversity (Crowell et al. 2006, Valley et al. 2006), and the impacts on fish populations (Pothoven et al. 1999). Concerns over fish-plant and other biotic interactions following use of fluridone have encouraged further research efforts in this area (Sammons et al. 2003, 2005, Bremigan et al. 2005, Harman et al. 2005).

Standard risk assessments are used to evaluate the potential impact of herbicides to non-target species in support of the registration process. Although non-target toxicity data are generated for numerous vertebrate and invertebrate aquatic species in support of national Section 3 registrations for aquatic herbicides, there are often specific concerns related to treatment within individual states, individual water bodies, or with use of specific herbicides. Some state programs (e.g., California, New York, and Washington) have developed environmental impact statements and biological opinions related to risks and benefits associated with specific herbicides and other management techniques, as well as costly monitoring issues surrounding pesticide uses in waters of the western U.S. court-imposed via the National Pollution Discharge Elimination System (NPDES) decision. Specific concerns are often related to potential toxicity to non-target organisms (plants or animals) or rare, threatened, or endangered species in specific regions of the U.S. In some cases, these concerns can lead to additional selectivity testing on a specific plant species to support treatments (Nelson et al. 2002). Regional concerns over salmon populations in the western U.S. required that additional toxicity testing be conducted on surrogate salmonid species. Given increasing concerns by the public over the use of chemical pest control in general, specific herbicide, lake, or species issues are likely to increase in the future. Mechanisms for addressing these concerns, in addition to standard risk assessment tools, need to be investigated as funding and resources are not available to support specific studies to address every concern.

Real-time Monitoring of Aqueous Herbicide Residues to Guide Operational Treatments

During the late 1980s and throughout the 1990s, the link between herbicide efficacy and CET relationships was firmly established at the laboratory scale (Getsinger 1998). The high cost of traditional herbicide residue monitoring, and time lag in securing analytical results, led research groups to use the fluorescent dye rhodamine WT (RWT) to simulate the movement of herbicides through real-time monitoring and tracking of RWT concentrations (Fox et al. 1991, 1993, 2002, Fox and Haller 1992, Turner et al. 1994). This work provided key information regarding the movement and distribution of herbicides in the water column in relation to the size and shape of treatment blocks, vertical distribution of residues due to thermal gradients, residue distribution in relation to plant density and structure, and the role that wind intensity and direction could play in the dispersion of residues. While dye studies provided valuable information on the short-term nature of aqueous herbicide residues and could be correlated with herbicide concentrations, they were not practical for routine operational use.

Some limited use of enzyme-linked immunosorbent assay (ELISA) methods were employed in California in the mid-1980s to monitor water residues in rice production and irrigation canals (bensulfuron-methyl), and aquatic weed control programs (2,4-D) (L. Anderson, USDA-ARS, Davis, CA, pers. comm.). However, during the mid-1990s an ELISA method was developed by industry (SePRO Corporation, Carmel, IN) to support the wide-spread use of fluridone. This technique could provide quantification of aqueous fluridone residues down to 1 µg L^{-1} (fluridone is labeled for use up to a maximum of 150 µg L^{-1}). The ability to determine fluridone residues in conjunction with operational use of the herbicide greatly expanded the knowledge of fluridone use and led to important changes in the use pattern of the molecule (Netherland et al. 2002). The fluridone ELISA allowed resource managers to monitor and document whole-lake treatments to within 1 µg L^{-1} of nominal concentrations. Moreover, this testing allowed for application of additional treatments termed “bump, split, or booster applications” to maintain aqueous fluridone residues at desired concentrations over time (Getsinger et al. 2002). Water sampling also demonstrated that following thermal stratification of northern lakes, fluridone residues would remain in the epilimnion. This expanded the use of fluridone because it significantly reduced the volume of water to be treated, reducing both chemical input and treatment costs. The development and operational use of the fluridone ELISA was critical to improving recommendations for whole-lake use and selective treatment strategies (see next section).

In addition to fluridone, an immunoassay was developed for triclopyr, and data from this ELISA was used for the first time to support the registration of an aquatic herbicide (Getsinger et al. 2000). Quantitative ELISA's are currently available for fluridone, triclopyr, endothall, and 2,4-D, and one is being developed for penoxsulam; a qualitative ELISA is being developed for diquat. With the exception of fluridone, ELISA has largely been used in operational treatments to determine when various water use restrictions (e.g., irrigation, potable use) can be lifted. Nonetheless, the ELISA tests have already proven to be valuable research tools, and this work suggests numerous potential operational uses for optimizing the efficacy of herbicide applications in challenging, high-flow environments. The significant reduction in cost of the ELISA compared to traditional analytical techniques allows for increased sampling efforts to determine real-time field dissipation as well as residue behavior following application of various herbicide formulations. The availability of numerous ELISA kits for aquatic herbicides will be invaluable for future research and operational implementation of these products.

Whole-lake Manipulations and a Shift to Species-selective Control

During the 1990s, improved knowledge of herbicide CET relationships and herbicide residue patterns led to two major changes in the management of submersed plants. While numerous large-scale fluridone applications were conducted in the late 1980s and early 1990s, there was limited information on refinement of treatment rates, no residue verification, and limited efforts to document injury to non-target vegetation.

Following many early whole-lake fluridone applications, resource managers noted that the targeted invasive plants were controlled; however, there was often considerable injury to non-target vegetation with no confirmation of residues. This concern was especially heightened in the native plant-rich regions of the upper Midwest and Northeast U.S.

Outdoor mesocosm studies demonstrated that fluridone application rates and treatment timing were the most important factors in determining selectivity to a suite of submersed species (Netherland et al. 1997). In combination with the knowledge that the target invasive plant Eurasian watermilfoil was sensitive to very low concentrations of fluridone (Netherland and Getsinger 1995b), strategies were devised to treat whole-lakes at low fluridone levels to enhance treatment selectivity. These early operational trials resulted in valuable field information regarding susceptible and tolerant plant species (Smith and Pullman 1997); however, there were limited water residue data to verify that aqueous concentrations of the herbicide were actually being met. The concept of whole-lake management became more widely accepted in the late 1990s due to the inherent properties of the fluridone molecule (described above) and improved information regarding target species susceptibility to fluridone concentrations. Subsequent research efforts in Michigan and Vermont provided more detailed information on the status of pretreatment vegetation, aqueous fluridone residues throughout the treated areas, long-term post-treatment response of the target and native vegetation, and response of sport fish populations and water quality (Getsinger et al. 2002, Madsen et al. 2002, Netherland et al. 2002, Valley and Bremigan 2002, Bremigan et al. 2005). Additionally, research continued into developing strategies to maximize selectivity through treatment timing (Koschnick and Haller 1998, Pedlow et al. 2006). The concept of treating a whole-lake to target an invasive plant using low concentrations of fluridone to protect native vegetation is now a widely accepted practice throughout the aquatic plant management industry.

Recent research in the area of fluridone selectivity suggests that lake trophic status and native plant species richness present at treatment may impact treatment outcomes in northern lakes (Crowell et al. 2006, Valley et al. 2006). In lakes that support mostly fluridone-tolerant native species, any direct treatment impact on lake ecology may be different than systems comprised of mostly fluridone-susceptible species. In addition, species richness might be artificially low at the time of fluridone application in lakes where invasives have potentially out-competed desirable native species (Boylen et al. 1999, Madsen et al. 1991) Species composition at the time of fluridone application may be critical in management outcomes, but whether composition and richness are correlated to trophic status in northern-tier lakes needs further investigation. There have also been investigations regarding the long-term effects on submersed vegetation and on biotic richness following repeated whole-lake fluridone applications (Harman et al. 2005, Crowell et al. 2006). Recent fishery research in southern reservoirs has focused on the implications of large-scale removal of hydrilla on largemouth bass populations following a fluridone treatment (Sammons et al. 2005).

Over the past decade there has been a renewed emphasis on evaluating the selective properties of older contact herbicides such as endothall in both northern and southern submersed plant communities (Skogerboe and Getsinger 2000, 2001, Parsons et al. 2004), and the systemic products triclopyr and 2,4-D (Getsinger et al. 1997, Hofstra and Clayton 2001, Parsons et al. 2001). The importance of using aquatic herbicides in the most selective manner possible to meet specific plant management objectives cannot be overstated. Any future research with either new or existing herbicides will likely include plant species selectivity as a major component of the research.

Herbicide Resistant Hydrilla

One unexpected development in aquatic plant management was the discovery of resistance to fluridone by the submersed invasive plant hydrilla (Michel et al. 2004). The idea that an asexual population (female strain of dioecious hydrilla) could develop widespread resistance to an herbicide was thought to be highly unlikely. The importance of this discovery is significant because hydrilla represented the first aquatic plant to develop resistance to an aquatic herbicide, the first asexual plant population to develop a somatic mutation leading to widespread resistance in the field, and the first documentation of resistance to the class of herbicides known as PDS inhibitors (Arias et al. 2005, Dayan and Netherland 2005). The occurrence of a resistant strain of hydrilla is related to a combination of several factors: (1) hydrilla is extremely sensitive to fluridone; (2) the nature of the fluridone molecule results in long-term exposure to slowly declining residues; (3) fluridone targets a single site of action; (4) a large hydrilla infestation can have millions of actively growing meristems; (5) fluridone was used repeatedly (often annually) for the large-scale management of hydrilla; (6) there were no other systemic modes of action to alternate with fluridone; (7) hydrilla populations were at historically high levels; and (8) a point mutation in the PDS enzyme can confer fluridone resistance (Dayan and Netherland 2005).

Fluridone-resistant hydrilla is currently found only within the state of Florida; however, it is widespread within the state and widely established in many large lakes (>400 ha). Given the historical spread of hydrilla within and outside of Florida, the likelihood is high that fluridone resistant strains will spread on an intra- and interstate basis. The spread of fluridone-resistant hydrilla has resulted in significant changes in the Florida Department of Environmental Protection's large-scale hydrilla management program. Professionals from various federal, state, and local natural resource management agencies recently held meetings to discuss the issue of fluridone resistance and hydrilla management, and several recommendations came out of these discussions (Netherland et al. 2005b), including: (1) discourage consecutive-year applications of fluridone in the same water body; (2) develop resistance management strategies to ensure that flurdione-resistant hydrilla does not develop dual resistance to other products; and (3) in addition to rotational application schemes with fluridone and other single site-of-action herbicides, develop new contact herbicides that can be rotated with older contact chemistries.

A diquat-resistant strain of duckweed, dotted duckweed (*Landoltia punctata* [G.Meyer] D. H. Les and D. J. Crawford), in Florida (Koschnick et al. 2006) has also been documented. It is becoming more evident that herbicide resistance is not limited to terrestrial agricultural systems, and therefore resistance must be considered in the development of new aquatic herbicides, and the use of both new and older chemistries. This process is especially pertinent because new herbicide modes of action being evaluated in aquatics will likely be single site-of-action compounds that target specific plant enzyme systems (Koschnick et al. 2004, 2007). While this specificity for plant enzymes results in herbicides having reduced non-target toxicity, experience with fluridone and similar herbicides used for terrestrial weed control also suggest a strong selection pressure for resistant strains to occur exerted by herbicides with a single site of action.

In addition to herbicide resistance, hybridization of invasive and native submersed watermilfoil species has been documented (Moody and Les 2002, 2006, Poovey et al. 2005). Moreover, recent invasions and expansion of native plants, variable milfoil (*Myriophyllum heterophyllum* Michx) and fanwort (*Cabomba caroliniana* L.), into northern latitude states is a source of concern for aquatic resource managers (Nelson et al. 2002, Getsinger et al. 2003). In the south, the invasive plant hygrophila (*Hygrophila polysperma*) has become problematic in flood control canals of Florida, and has proven to be tolerant of all forms of aquatic management including mechanical, grass carp, and use of registered herbicides (Sutton 1995). Continued expansion of hydrilla and Eurasian milfoil, hybridization, development of herbicide resistance, and the emergence of new weed species all point to the need for continued research for environmentally sound control strategies.

Interactions with U.S. Environmental Protection Agency

From 1977 through 2001, only two new active ingredients received Section 3 labels for use in aquatic sites throughout the U.S.: glyphosate in 1977 and fluridone in 1986 (Table 1). In addition, at the end of that 25-year period, only six active ingredients had national, Section 3 aquatic registrations. However, from 2002 through 2007, five new Section 3 labels were approved: triclopyr, 2002; imazapyr, 2003; carfentrazone-ethyl, 2005; penoxsulam, 2007, and imazamox 2008. Four other products received special aquatic use labels: bispyribac-sodium, EUP, 2006; flumioxizin, EUP, 2006; quinclorac, EUP, 2007; and metsulfuron-methyl, Section 24c FL, 2004.

Several factors converged to initiate the resurgence in the development and registration of new aquatic herbicides. One key ingredient was the discovery of fluridone resistant hydrilla. The ability to manage important water resources in Florida and other states would be hindered if other effective and economical tools were not developed to supplement fluridone. In addition, resistance development by hydrilla and dotted duckweed suggests that other major weed species may also have this capacity.

Another important factor was the business climate created by the advent of glyphosate-resistant row crops, such as Roundup©-ready soybeans, corn, cotton. This occurrence greatly limited market share of competitive crop protection products in the major row crop commodity arena. As a consequence, the loss of market share in row crop herbicides made minor-use markets, such as noncrop lands and aquatics, more attractive to registrants. The old economic paradigm of high research, development, and registration expenses versus a low return on investment in a specialty market (Gallagher and Haller 1990) was falling by the wayside.

A linchpin in moving the aquatic registration process forward was the regulatory community acceptance of the pressing need for new herbicides and the realization that these products could address invasive weed problems while providing an acceptable risk to human health and the environment. For nearly three decades, technical communication and collaboration between the third-party research community (agency and academia) and respective registrants was operating on an "as needed" basis. While communication between the registrants and the regulatory community functioned as required by laws and policies during this same time period, meaningful and consistent dialogue between aquatics researchers and regulators was lacking.

In the mid 1990s, recognition of this communication gap by the research community, including such groups as the U.S. Army Corps of Engineers, the University of Florida, and the U.S. Department of Agriculture (USDA), led to a technical and educational outreach initiative with the USEPA Office of Pesticide Programs (OPP). By 2004, collaboration and information exchange between the researchers and the USEPA-OPP was institutionalized with the formation of a Federal Aquatic Herbicide Work Group and a unique relationship with the USDA's IR-4 Project concerning the registration of minor use herbicides. These federal government interactions were then blended with key state regulatory and natural resource management agencies and evolved into partnerships with scientific societies and nonprofit organizations, such as the Weed Science Society of America, the Aquatic Plant Management Society, and the Aquatic Ecosystem Restoration Foundation. Technology transfer focused on the need for new products, the re-registration of old chemistries, use patterns in aquatic sites, improvements in labeling, revisions to use restrictions that allowed for selective control of target weeds, and protection of human health and the environment (Netherland et al. 2005a). Due to this cooperation between industry, regulators, and researchers, understanding the need for aquatic herbicide registrations and their responsible use is at its highest point in history. This cooperation will be increasingly critical as the USEPA moves toward more complex pesticide regulations concerning impacts on threatened and endangered species.

SETTING PRIORITIES FOR FUTURE RESEARCH

Following discussion of the research advances, a list of research priorities for the development and use of herbicides in aquatic environments over the next five years was established. Input was obtained from the authors as well as from several aquatic resource managers within the U.S. Based on recent progress with registered products; research on herbicide selectivity, herbicide residue behavior, and resistance development should continue to be pursued. Moreover, close cooperation with regulatory agencies to insure that public safety and environmental concerns are adequately addressed must be continued.

A major challenge in developing a national research strategy for chemical control is the myriad of problems and management approaches that exist on a state-by-state or regional basis. In view of this, seven key areas for future research were identified. Based on the potential for bias related to a particular research discipline or regional need, these topics were not ranked. Research priorities and future challenges include:

A. Developing improved methods for evaluating non-target impacts of herbicides with emphasis on species of local concern or threatened and endangered (T&E) species.

B. Improving herbicide performance in flowing-water environments, including irrigation canals.

C. Screening and developing new herbicides to supplement fluridone for large-scale or whole-lake management approaches.

D. Screening and developing new organic algaecides to supplement the use of copper-based compounds.

E. Developing risk assessment tools to educate the public on the risks of invasive species and chemical management options.

F. Increasing cooperative research with ecologists and fisheries scientists to evaluate the long-term impacts of invasive species introductions and herbicide programs on native plant assemblages, water quality, and fish populations.

G. Improving integration of chemical control technology with other aquatic plant management disciplines.

Developing Improved Methods to Evaluate Non-target Impacts of Herbicides with Emphasis on Species of Local Concern or Threatened and Endangered (T&E)

Toxicology Challenges

1. Improving data development for non-target organisms (plant and animal) with an emphasis on developing strategies to address T&E species issues. This process could include development and verification of surrogate species to deal with U.S. Endangered Species Act toxicological information gaps and issues of limited populations of T&E listed species to test.
2. Addressing specific concerns for the potential non-target toxicity of formulated and end products (e.g., adjuvants and tank mixtures).
3. Documenting a regional basis of the actual field exposures following various herbicide applications and relating these exposures to current toxicity data. Use patterns, weed control objectives and specific concerns can vary dramatically on a regional basis.
4. Due to high plant specificity and potency, newly registered compounds such as enzyme-specific inhibitors, addressing the concerns for T&E plant species and potential for impacts on non-target emergent plant species following submersed applications.

Improving Herbicide Performance in Flowing-water Environments, Including Irrigation Canals

Challenges in Flowing-water Environments

1. Review labeling for currently registered products to determine if language changes can include rivers or flowing-water environments. If not, identify studies necessary to support flowing-water use.
2. Limitation of products other than copper and acrolein (2-propenal) due to irrigation concerns (phytotoxicity, crop residues or tolerances).
   a. Encourage companies to develop crop-tolerance information and interact with lead research, governmental, and resource agencies such as IR-4, to facilitate and assist in the process.
   b. Develop application techniques and efficacy data for use in high-flow environments that would include sediment-active herbicides and plant growth regulators for pre-emergent plant control in dewatered irrigation canals.
3. Emphasize products that can be used in spot treatments or highly dynamic waters within screening programs for new product development. Small-scale treatments in largely static waters can also be subject to rapid dilution due to dispersion. Products that have short exposure requirements could be effectively used in early detection and rapid response programs.
4. Evaluate formulations or application techniques that will increase exposure time and improve efficacy in flowing-water situations. Again, this technolo-

gy could also have utility for spot applications in early detection programs designed to prevent invasive plants from expanding. These small-scale treatments would rely on improved surveillance and reduce the overall use of chemicals.

Screening and Developing New Herbicides to Supplement Fluridone for Large-scale or Whole-lake Management Approaches

Challenges in Efficacy and Species-selective Control

1. Focus screening efforts on species selectivity and non-target issues. A regional suite of non-target native species should be identified as a standard for testing protocols.
2. Develop susceptibility data for key native plants, comparable to the database for hydrilla and Eurasian watermilfoil. Cooperation with regional entities will be required to identify the key submersed and emergent species for evaluation.
3. Develop resistance management guidelines for existing and new chemical tools.
   a. Develop and implement resistance management guidelines for the new ALS products registered for aquatic sites.
   b. Provide information to regional managers on how to use or rotate chemical products to prevent resistance development of herbicides. For example, weed control for a California or Washington eradication strategy is different than managing for low levels of weeds on large waterbodies in Florida.
   c. Identify and support registration of new herbicides that target different enzymes or sites of action. This will require developing improved screening procedures for native and submersed species to effectively assess a wide variety of compounds.

Screening and Developing New Organic Algaecides to Supplement the Use of Copper-based Compounds

Challenges in Algal Research and Management

1. Involve researchers that have focused on aquatic plant management in evaluating new chemical technologies to address HAB and nuisance algae, which are becoming more wide spread in ponds, lakes, and reservoirs across the country.
   a. Encourage industry to make herbicides available for screening as potential algaecides to supplement copper and other management techniques.
   b. Evaluate compounds for both broad-spectrum and selective algal properties. While traditional broad-spectrum compounds (e.g., the organic algaecides simazine and diuron) have some desirable properties, there is also potential that some compounds that serve as selective herbicides may also serve as selective algaecides. The ability to remove or reduce harmful or nuisance algae without impacting desirable species would have substantial benefit. Moreover, compounds that are selective on algae would likely be of a low order of toxicity to non-target organisms.
   c. Evaluate impacts of certain cyanobacteria (blue-green algae) on submersed macrophyte growth with respect to toxin production or allelopathy, and light or resource competition.

Developing Risk Assessment Tools to Educate the Public on the Risks of Invasive Species and Chemical Management Options

Challenges of Risk Assessment and Public Education

1. Develop methods or models to conduct a risk assessment for aquatics that evaluate the impacts of the invasive species, management alternatives, or a no action alternative. Risk assessments are becoming more accepted in the field of toxicology and play a role in the USEPA herbicide registration process.
2. Review invasive plant management education and outreach strategies and determine the best approach for educating the public.
3. Develop database for performance of herbicides to control high-risk invasive species not yet introduced to U.S. waters as effective rapid responses to new invasions.

Increasing Cooperative Research with Ecologists and Fisheries Scientists To Evaluate Long-term Impacts of Invasive Species Introductions and Herbicide Programs on Native Plant Assemblages, Water Quality, and Fish Populations

Challenges of Partial Large-scale and Whole-lake Management

Ecologists:

1. Develop standardized and cost-effective method to adequately assess aquatic vegetation for both managed and non-managed systems.
2. Develop improved methods for detecting impacts of chemical management on native and invasive plants, as well as methods for detecting impacts of invasive plants on the native vegetation.
3. Develop a weight-of-evidence model for significance of field study results versus true replication because true replication of water bodies for study purposes is frequently not possible.
4. Focus resources to monitor impacts associated with invasive species introductions to aquatic systems. Too often, impacts are assumed or anecdotal.

Fisheries Scientists:

1. Developing a better understanding of aquatic plant and fish interactions within the littoral zones of water bodies.

2. Determining impacts of aquatic plant communities heavily dominated by invasive weeds vs. diverse native plant assemblages on fisheries (sport and rough) and invertebrates, both on a population and community level.
3. Defining the optimum aquatic plant assemblage (abundance and diversity) required to maximize a healthy fisheries in inland lakes, and impacts of invasive species on this management objective.

Improving Integration of Chemical Control Technology with Other Aquatic Plant Management Disciplines

Challenges of Integrated Management:

1. Develop innovative strategies that utilize chemical control in combination with alternative techniques (e.g., pathogens, insects, mechanical harvesters) to selectively control invasive plants, when herbicides alone are not a viable option.
2. Examine potential integration of plant growth regulators, herbicides, and biological control components.
3. Use integrated management approaches to develop programs for long-term habitat restoration.

We recognize that these research topics reflect the current situation, and given the dynamics of aquatic plant management, unforeseen circumstances or development of new technologies will likely result in emphasizing areas of research not included in this review. However, we believe that research to address the challenges described above will fill key information gaps and will ultimately provide economical and environmentally responsible solutions to the selective control of invasive aquatic plants and algae. For example, a non-lethal chemical strategy, plant growth regulation (PGR), was considered for aquatic plant management in the 1980s (Anderson 1986, 1988, Getsinger 1988; Lembi and Netherland 1988). While some have suggested that the PGR approach be pursued, we have not included them in this discussion but recommend that this strategy be considered more comprehensively in another venue.

We also note that without a long-term and consistent commitment of adequate resources (e.g., investigators, facilities, and funds) by agencies or institutions, the ability to conduct the required research and provide the needed solutions will not be fully achieved. Finally, the considerable problems posed by invasive aquatic plants cannot be overcome unless a truly integrated cross-discipline effort is conducted, including contributions from herbicide specialists, toxicologists, aquatic ecologists, fisheries scientists, and public policy makers.

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