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Comparison of Daytime and Night-time Applications of Diquat and Carfentrazone-ethyl for Control of Parrotfeather and Eurasian Watermilfoil

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INTRODUCTION

Parrotfeather (*Myriophyllum aquaticum* Vell. Verdc.) and Eurasian watermilfoil (*Myriophyllum spicatum* L.) are non-native invasive species that are often difficult to control. Once established, these species thrive in a variety of environmental conditions and have shown resiliency to control techniques. To date, chemical control has been the most effective method for managing infestations of these species. Contact herbicides such as diquat (6,7-dihydrodipyrido (1,2-a:2',1'-c) pyrazinedium dibromide) and carfentrazone-ethyl (a,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoic acid, ethyl ester) are used to rapidly kill standing biomass (Westerdahl and Getsinger 1988, Moreira et al. 1999). These rapid-acting contact herbicides often provide only short-term control and significant regrowth of non-impacted plant tissues is common.

Diquat is a photosynthesis inhibitor that interferes with electron flow by accepting electrons from photosystem I. The interference of electron flow leads to the production of superoxide radicals that ultimately results in the peroxidation of cell membranes (Hess 2000, Senseman 2007). Diquat symptoms appear within hours of application in full sunlight, with complete foliar necrosis by 1 to 3 days after application (Senseman 2007). Diquat has shown excellent efficacy on Eurasian watermilfoil where 90 to 100% control was achieved under short half life scenarios (Skogerboe et al. 2006); however, there are few published accounts of its efficacy on parrotfeather.

Carfentrazone-ethyl is a protoporphyrinogen oxidase inhibitor approved for use in aquatic systems in 2004. Carfentrazone-ethyl competes with protoporphyrinogen for binding sites on the protoporphyrinogen oxidase enzyme (Devine et al. 1993, Hess 2000). This competition causes protoporphyrinogen to leak into the cytoplasm and, in the presence of light, to be converted to protoporphyrin IX. Protoporphyrin IX reacts with oxygen in the presence of light to form singlet oxygen radicals that cause the oxidation of lipid membranes, resulting in cell death (Devine et al. 1993, Hess 2000). Foliar desiccation is rapid, and susceptible plants become necrotic and die within a few days after treatment (Senseman 2007). Carfentrazone-ethyl has shown variable control of parrotfeather where ratings ranged from 29 to 70% (Glomski et al. 2006, Gray et al. 2007). Eurasian watermilfoil control was ≤70% in those same studies.

Both diquat and carfentrazone-ethyl require sunlight for activity, so when applied during daylight hours, herbicide symptoms appear rapidly at the point of contact. The rapid destruction of plant tissues by these herbicides results in self-limited translocation of the herbicide in the plant and subsequently limits damage to the point of contact (Slade and Bell 1966, Funderburk and Bozarth 1967, Senseman 2007). A possible method to increase herbicide uptake and translocation into target plants may be to apply these herbicides at night to allow greater herbicide movement into target plants prior to light activation and significant tissue damage. Baldwin (1963) reported that a period of darkness following diquat applications resulted in considerable amounts of herbicide being transported away from the point of contact. This relationship was also noted with paraquat (*N,N'*-dimethyl-4,4'-bipyridinium dichloride) (Slade and Bell 1966). The objective of this study was to compare the effectiveness of subsurface applications of diquat and carfentrazone-ethyl applied to parrotfeather and Eurasian watermilfoil under light and dark conditions. This study is a first account of diquat efficacy on parrotfeather, especially as a subsurface application.

MATERIALS AND METHODS

The study was conducted in an outdoor mesocosm facility at the R. R. Foil Plant Science Research Center, Mississippi State University, Starkville, Mississippi, for 6 weeks in September to October 2006. The study was conducted as a randomized complete block design with two rates of diquat, two rates of carfentrazone-ethyl, two application times, and an untreated reference. Each treatment was replicated three times. Parrotfeather and Eurasian watermilfoil used in this study were planted from greenhouse stock maintained at Mississippi

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State University. Planting consisted of placing two 20-cm apical shoots into 3.78-L plastic pots. Pots were filled with potting medium (a mixture of top soil, loam, and masonry sand), amended with 2 g L^{-1} of 19–6–12 Osmocote® fertilizer, and placed into the tanks. Three pots of each plant species were placed into 378-L tanks and filled with 245 L of water. Both plant species were allowed to grow for approximately 2 weeks or until plant growth was at or near the water surface.

Following the pretreatment growth period, herbicide applications were made to the water column. A concentrated aqueous solution was applied to each tank such that, when diluted in 245 L, it provided the desired herbicide concentration. Diquat was applied as Reward®[4] at target concentrations of 0.37 mg ai L^{-1} and 0.19 mg ai L^{-1}, the maximum and half the maximum label rates. Carfentrazone-ethyl was applied as Stingray®[5] at target concentrations of 0.20 mg ai L^{-1} and 0.10 mg ai L^{-1}, the maximum and half the maximum label rates. Herbicide applications were made between 8:00 and 9:00 am on a sunny day in tanks receiving light exposure; and between 8:00 and 9:00 pm for tanks receiving dark exposure. This allowed for a 12 h dark exposure period for plants treated at night prior to light activation. After 24 h, the water volume in each tank was replaced with clean water to purge any remaining herbicide from the tanks.

At 4 weeks after treatment (WAT) viable (green tissue) aboveground plant material was harvested, dried, weighed, and compared to the untreated reference plants to assess herbicide efficacy. A General Linear Model was used in SAS® to determine treatment differences and means separated with a Fisher's Protected LSD analysis. A two-way Analysis of Variance was not used due to an unbalanced experimental design with respect to the number of reference tanks. All analyses were conducted within species at a $p = 0.05$ level of significance.

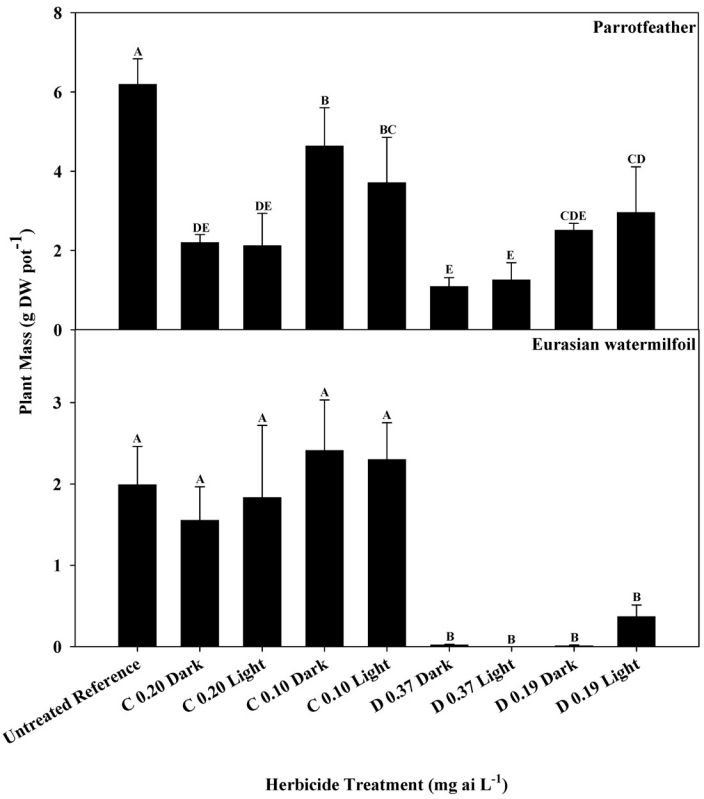

Figure 1. Mean (±1 SE) plant mass of parrotfeather and Eurasian watermilfoil 4 WAT with carfentrazone-ethyl (C) and diquat (D) applied under light and dark conditions. Analyses were conducted within species and between herbicides and rates. Bars sharing the same letter are not significantly different according to Fisher's Protected LSD analysis at a $p = 0.05$.

RESULTS AND DISCUSSION

Parrotfeather

In all treatments, diquat at each concentration and application time significantly reduced biomass of parrotfeather by 52 to 82% across diquat concentrations (Figure 1). Allowing for a dark exposure after herbicide application did not result in increased efficacy of diquat on parrotfeather at the concentrations tested. Although parrotfeather biomass was reduced with respect to untreated plants, regrowth was evident, and plants would have recovered given sufficient time. Plant recovery was occurring through regrowth via root crowns and the formation of new shoots from the nodes of surviving plants.

Interestingly, parrotfeather treated with diquat formed a necrotic region on the stolon at the air-water interface. The necrotic region caused the abscission of the stolon resulting in fragmentation of emergent shoots. These fragments where likely viable 4 WAT as they were developing adventitious roots. Fragments were collected and included in plant mass determinations. It is unclear as to the mechanism causing this fragmentation, but it appears that diquat movement in the xylem stopped at the air–water interface. A possible explanation may be differences in the anatomical structure of submersed and emergent parrotfeather tissues (Sutton and Bingham 1973) resulting in the incomplete movement of the herbicide; however, more research is needed to further investigate this mechanism.

The use of carfentrazone-ethyl was also effective at reducing parrotfeather at both concentrations and application times (Figure 1). A 64 and 65% reduction in parrotfeather biomass was obtained when carfentrazone-ethyl was applied at 0.20 mg ai L^{-1} during a dark and light exposure period, respectively. Similar to diquat, the dark exposure did not result in increased efficacy of carfentrazone-ethyl against parrotfeather. Gray et al. (2007) reported similar biomass reductions of parrotfeather (63%) using carfentrazone-ethyl at 0.20 mg ai L^{-1}. Unlike the present study where a 24-h contact time was used, Gray et al. (2007) used a static exposure. Data from this study suggest that increasing the exposure time of carfentrazone-ethyl has little effect on increasing the control of parrotfeather. However, in both this study and Gray et al. (2007) the pH of the water likely impacted the efficacy of carfentrazone-ethyl more so than the exposure time used. The water used in this study was taken from an irrigation reservoir where the pH fluctuates between 7.8 and 9. A pH approaching 9 would result in a half life of approximately 3 to 4 hours, reducing the contact of the plants to a lethal dose of the herbicide (Ngim and Crosby 2001).

Eurasian watermilfoil

Eurasian watermilfoil was highly susceptible to diquat, with 85 to 100% biomass reductions for all diquat treatments (Figure 1). The dark exposure period did not increase diquat efficacy on Eurasian watermilfoil as all diquat treatments were similar. Reductions in Eurasian watermilfoil biomass of 97% to 100% was achieved using similar diquat concentrations at half lives of 2.5 and 4.5 h, which would equate to exposure times much less than that used in this study (Skogerboe et al. 2006). Conversely, carfentrazone-ethyl was not efficacious against Eurasian watermilfoil. Biomass of treated plants and the untreated reference plants were statistically similar. Biomass reductions in this study were only 25 and 37% for the 0.20 mg ai L^{-1} light and dark treatments, respectively. These data contrast those reported by Gray et al. (2007) where carfentrazone-ethyl resulted in complete control (100% biomass reduction) of Eurasian watermilfoil at a concentration of 0.20 mg ai L^{-1}.

Absorption and translocation of herbicides were not directly measured in this study; however, if greater absorption or translocation were occurring in plants treated in the dark, then increased control should have occurred. Our results suggest that a period of darkness following applications of diquat and carfentrazone-ethyl did not necessarily increase herbicide movement in treated plants because control was not different among treatments. The lack of movement of bipyridinium herbicides has been documented in terrestrial plants where a 12-h dark period following paraquat and diquat applications did not enhance movement of either herbicide in wheat (Coats et al. 1966). The movement of paraquat out of treated leaves of capeweed (*Arctotheca calendula*) was slow in the dark where after 72 h, 80% of the paraquat was still in the treated leaves (Soar et al. 2003). Preston et al. (2005) reported <4% of absorbed paraquat was translocated in a basipetal direction in susceptible plants. Therefore, a period of dark exposure may not be an important means of diquat or carfentrazone-ethyl movement as previously thought.

Based on the results of this study there was no increase in efficacy of diquat or carfentrazone-ethyl on parrotfeather or Eurasian watermilfoil with treatments made in the dark. The pH of the water used in this study likely reduced the half life of carfentrazone-ethyl in the tanks, thereby reducing overall herbicide efficacy, especially with respect to Eurasian watermilfoil. The use of a shorter herbicide exposure time and or lower herbicide rates may have allowed for the discerning of differences. For example, an 8-h exposure time would have allowed morning applications to be completely in the light and night applications completely in the dark. Future research may be directed toward determining light–dark exposure relationships for floating species using foliar herbicide applications.

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