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**ALTERNATIVES TO METHYL BROMIDE FOR WEED CONTROL IN PERENNIAL
ORNAMENTAL CROPS AND CONIFER SEEDLINGS**

By

Robert Egon Uhlig

A THESIS

**Submitted to
Michigan State University
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ABSTRACT

ALTERNATIVES TO METHYL BROMIDE FOR WEED CONTROL IN PERENNIAL ORNAMENTAL CROPS AND CONIFER SEEDLINGS

By

Robert Egon Uhlig

The soil fumigant methyl bromide is being phased out in accordance with the Montreal Protocol and will not be available in the future. Experiments were conducted to identify fumigants and herbicides to replace methyl bromide for weed control in conifers and ornamental crops grown in the field and in containers under Michigan conditions. The fumigants methyl iodide, metham sodium, 1,3-dichloropropene, dazomet, and chloropicrin were evaluated in a field experiment. All of these fumigants provided good weed control, except methyl iodide 50% plus chloropicrin 50% (224 kg/ha) tarped and metham sodium (701 L/ha, 1:4 water) not tarped. *Euphorbia polychroma*, *Echinops bannaticus* 'Blue Globe', *Lavandula angustifolia* 'Hidcote Blue', *Hosta fortunei* 'Twilight PP14040', *Artemisia schmidtiana* 'Silver Mound', *Chrysanthemum x superbum* 'Snow Lady' and *Coreopsis verticillata* 'Moon Beam' growth was not affected by any of the fumigants. Herbicides were applied to several ornamental and conifer species to evaluate crop tolerance and weed control in the field and containers. There was considerable variability in crop tolerance among the species evaluated. The woody ornamental species *Picea glauca* var. 'Dwarf Alberta', *Taxus x media* var. 'Brownii', and *Thuja occidentalis* var. 'Holmstrup' were tolerant of most herbicide treatments, while other species were sensitive to one or more herbicides. Terbacil gave excellent weed control, but caused injury on most species. Flumioxazin and isoxaben plus trifluralin were the safest treatments on the species evaluated and gave good weed control.

To the memory of
Ing. Agr. Harry Uhlig

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CHAPTER I: INTRODUCTION

Methyl Bromide (MB) is a toxic gas used to control pests and diseases since before World War II. In recent decades MB use as a soil fumigant has increased steadily. Between 1984 and 1992 world wide use increased 60% (Price 1996). MB is the most widely used fumigant in the world with 68,424 metric tons used in 1996. Almost half of this was used in the USA. Agriculture accounts for 70% of the use, 5 to 8% is used for quarantine purposes; 8% is used for perishable product treatment; and 12% is used for non-perishable product treatment (Ware 2000).

Oceanic sources, biomass burning, leaded gasoline combustion, structural fumigation, and agricultural applications contribute to MB emissions into the atmosphere. The relative contributions of anthropogenic and natural emissions to total atmospheric MB are not well known (Butler and Rodriguez 1996); however it was estimated that man-made sources account for 35% and natural sources account for 65% of the total MB in the atmosphere (Hanwant 1993).

Even though MB is in low concentration in the atmosphere (10 parts per trillion) and has a short lifetime in the atmosphere (one year), it contains bromine, a highly active ozone depletion compound, leading to a high ozone depletion potential in the stratosphere (Butler and Rodriguez 1996). The bromine atom released from the MB molecule in the stratosphere reacts with an ozone molecule (O_3) resulting in one oxygen (O_2) and one bromine oxide molecule. The last, reacts with another ozone molecule resulting in two molecules of oxygen and one atom of bromine which reacts with another ozone molecule. This chain reaction affects negatively ozone concentration in the stratosphere (Bird 2005).

Montreal Protocol on Substances that Deplete the Ozone under the United Nations Development Programme (UNDP) recognized MB as a chemical that contributes to depletion of the earth's ozone layer, which protects the earth from incoming UV radiation from the sun. Excessive UV radiation can denature protein and cause nucleic acid transformation, resulting in negative human health impacts. The Montreal protocol set a time frame to reduce manufacture and importation of MB, and phase it out in developed countries for agricultural uses. The protocol mandated a 25% reduction in 1999, 25% reduction in 2001, 20% reduction in 2003, and complete phase out in 2005. Developing countries have agreed to reduce most chlorofluorocarbon (CFC) consumption by 50% by 1 January 2005 and to fully eliminate these by 1 January 2010 (Anonymous 2004b).

Elimination of MB will cause economic losses to US agriculture. Research has been conducted on high value crops (tomatoes, strawberries, peppers, tobacco, and cucumbers) in search of alternatives for MB. Less research, however, has been done in the ornamentals nursery industry. There is a distinct need for research on MB alternatives for nurseries and greenhouse enterprises. Nursery and greenhouse production is the fastest growing segment in agriculture. Sales increased 30% in a seven years period (1991-1998) (Knox et al. 2003). Even though non-chemical methods of weed control are practiced, chemical methods are the most widely used in the ornamental nursery (Anonymous 2004a).

The objective of this research is to find alternative chemicals, either fumigants or herbicides that can replace MB for weed control in the ornamental industry. The information obtained will provide nurseries with complementary tools for weed control,

contributing to make them less dependable on MB and, reducing the negative impact of the elimination of MB.

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CHAPTER II: LITERATURE REVIEW

Ornamental industry

Nursery and greenhouse production represent the sixth largest agricultural commodity group in the United States. This is the fastest growing segment of U.S. agriculture; between 1991 and 1998 sales of this segment increased 30%. Nursery growth is due to the strong U.S. economy with the expansion in housing and increase of ornamental plant use (Knox et al. 2003).

Weeds cause an estimated 12% reduction in crop yield in United States agriculture, representing \$32 billion lost annually. In addition to direct losses, \$4 billion is spent on herbicides each year. The cost of weed control in lawns, gardens, and golf courses is estimated in \$36 billion per year (Pimentel et al. 2000).

Nursery economic losses due to weed infestations have been estimated at \$7,000 per acre. Weed species populations vary from nursery to nursery depending on many factors, such as environment, climate, and weed management (Table 1). Between \$500 and \$4,000 is spent per acre of containers for weed removal by hand (Mathers and Case 2003). However, hand-weeding is sometimes necessary regardless of preventive measures utilized for weed control (Knox et al. 2003).

Although growers try to implement non-chemical weed control practices, including mulches, plant density, and mechanical methods, chemicals are widely used for weed control in nurseries. Herbicides represent 20% (446,000 pounds) of the total amount of pesticides used in the nursery and floriculture industries in California, Florida, Michigan, Oregon, Pennsylvania, and Texas (Anonymous 2004a). A survey in Florida showed that 71% and 56% of nurseries use post-emergence and pre-emergence

herbicides, respectively, and almost half used both kinds of herbicide (Tatum and Thompson 1993).

Methyl Bromide

Methyl Bromide (MB) is a highly toxic gas that is formulated as a fumigant that is injected into soil before planting to control fungi, weeds, and nematodes. The United States utilizes about 60 million pounds each year. Approximately 75% of that amount is applied to soil, 11% is used after harvest of various commodities during storage and before export, and 6% is used in structures such as food processing plants, warehouses, and museums, as well as transport vehicles. The remaining 8% is used for production of other chemicals (Anonymous 2004b).

Methyl Bromide has been used since before World War II. The total amount used has increased steadily with a 60% increase between 1984 and 1992 (Price 1996). Among all fumigants, MB is the most popular, with 68,424 metric tons used in 1996, almost half of which was in the USA. Globally, 70% was used for pre-plant soil treatments in agriculture, 5 to 8% for quarantine purposes, 8% for perishable product treatment, and 12% for non-perishable products (Ware 2000).

Synthetic MB is prepared by refluxing methanol with excess hydrobromic acid in the presence of small amounts of sulfuric acid. It is a colorless gas at temperatures above 3.5 C and at low concentrations has no noticeable odor. Many different formulations of MB are available for various pest control objectives. Chloropicrin (2% v/v) is added as a warning gas.

Methyl bromide is a general biocide, making mode of action determination quite difficult to determine. In fact, the mode of action is not very well understood. Methylation of sulfhydryl groups and the following enzyme inactivation has been postulated to play an important role in its toxicity. MB affects a wide range of pests indicating that there is not a single toxic effect, and the process affected by MB has to be fundamental for living organisms. MB is highly soluble in lipids and has a high toxicity; it is lethal to rabbits at oral dosages (LD_{50}) 60 mg kg^{-1} (Price 1996).

Atmospheric MB originates from oceanic emissions and anthropogenic sources such as biomass burning, agricultural applications, leaded gasoline combustion, and structural fumigations. The relative contributions of anthropogenic and natural emissions to the total atmospheric MB are not well known (Butler and Rodriguez 1996). Hanwant (1993) estimated that man-made sources account for 35% and natural sources account for 65%. However, air and water concentration analysis of MB and methyl chloride in the southern ocean (latitudes 45° - 67° S, longitudes 144° - 139° E), suggested that there is no significant production of these gases in this region (Yvon-Lewis et al. 2004). Biomass burning represents a major contribution of bromine in the stratosphere and can be compared to the amount produced by ocean emissions and pesticides (Mano and Andreae 1994).

Methylation of soil organic matter may be the major pathway for MB degradation (Tao and Maciel 2002). This was confirmed by Xu et al. (2003), who found that incorporation into soil organic matter is the predominant pathway for transforming 1,3-D and MB in soil. Fulvic acid, one of the humic components of soil organic matter, plays a significant role in this process. According to the USDA 2004 annual report (Anonymous

2004b) hydrolysis is the major transformation pathway for fumigants; and soil pH, moisture, and organic content greatly affect this process. Even though fumigants are potent biocides, bacteria can be involved in MB degradation by directly oxidizing MB during the fumigation process (Miller et al. 1997). Furthermore, biodegradation of metham sodium by resistant Gram positive bacteria has been found in a field where this fumigant has been used for the last decade (Warton et al. 2001).

Little attention has been paid to MB due to its low concentration in the atmosphere (10 part per trillion) until recently, when stratospheric ozone depletion by MB was recognized. The ozone layer in the stratosphere is essential for protection of life on the planet from incoming ultra violet radiation from the sun (Roback 1996). Although MB has a short lifetime of one year in the atmosphere, it contains bromine, a powerful ozone removal compound, leading to high ozone depletion potential (ODP). When UV radiation strikes MB in the stratosphere, free bromine radicals are released. These combine with oxygen radicals released when UV radiation strike O_2 and O_3 (a natural process), making oxygen unavailable for combining with O_2 to form O_3 . This process disrupts the normal stratospheric balance between O_2 and O_3 (Bird 2005).

The Montreal Protocol on Substances that Deplete the Ozone under the United Nations Development Program (UNDP), ratified by 166 countries, is in charge of setting rules and regulations for safe country development. The Montreal Protocol defined MB as a chemical that contributes to depletion of the earth's ozone layer. Thus, manufacture and importation of MB will be phased out in developed countries for general agricultural uses based on 1996 levels. The reduction schedule is as follows: 25% reduction in 1999, 25% reduction in 2001, 20% reduction in 2003, and complete phase out in 2005

(Anonymous 2004b). Developing countries have agreed to reduce most chlorofluorocarbon (CFC) consumption by 50% by January 2005 and to fully eliminate these by January 2010 (Anonymous 2004c).

Many agricultural industries will be affected by the loss of MB. The ornamental and nursery industry in California is estimated to lose \$129 million and North Carolina \$14 million (Carpenter 2000). Michigan is the sixth largest nursery and floriculture producing state, with sales of \$629 million in 2002 (Anonymous 2002). Even though current application cost is approximately \$4,000 per hectare, the ornamental industry still relies on this product to achieve maximum yield and quality. Michigan used 220 metric tons of MB in 2000. The target objective of MB application varies between industries; for example, the herbaceous perennial ornamental industry targets first nematodes, then weeds and fungal diseases, and treats 90% of their planted surface with MB. On the other hand, the woody ornamental seedling industry focuses more on fungi, then weeds, and finally nematode control, applying the product to 75% of their acreage (Bird 2004). In the turf industry, MB fumigation is used primarily to eliminate weeds and to ensure genetic purity of turfgrasses, which is especially important in reconstruction and regressing of existing sites (Unruh et al. 2002). Growers obtain excellent weed, nematode, and fungi control with MB and depend on this fumigant to obtain desired yields in intensive and high value crop systems.

MB phase out will affect agricultural production significantly if no effective alternatives are found. At the moment, there are few fumigants that can substitute for MB. According to Duniway, (2002), "None of the chemical alternatives currently registered and available has the full spectrum of activity and versatility of MB as a pre-

plant soil fumigant. Methyl iodide and propargyl bromide probably have activity that most closely parallels that of MB in soil”. Studies confirm that no EPA-registered fumigant alternative to MB, applied alone or in combination for preplant turf soil fumigation, exists (Unruh et al. 2002).

Alternative fumigants

Fumigants that may not deplete the ozone layer have been studied thoroughly in recent years. Some prospective chemical alternatives to MB are metham sodium (MS), chloropicrin (CP), 1,3-dichloropropene (1,3-D), dazomet, methyl iodide also called iodomethane (MeI), propylene oxide (PPO), propargyl bromide, and sodium azide (Table 2).

MS is a broad spectrum biocide and may be used to control soil fungi, insects, nematodes, and weeds, although it is most effective as an herbicide. It decomposes to methyl isothiocyanate (MITC) which is the biocidal molecule. The transformation to MITC is the cause of inconsistent pest control (Unruh et al. 2002). MS has not always provided consistent control of soil-borne diseases and pests, and does not have the penetration capacity of MB (Messenger and Braun 2000). Control failure was also attributed to a build up of microorganisms that can degrade the chemical. Microorganisms with resistant stages were involved in the biodegradation of MITC in a field where MS has been used extensively for the past decade (Warton et al. 2001).

Unruh (2002) applied MS (748 L/ha), MS plus CP (748 L/ha: 168 kg/ha), tarped and not tarped, and MS plus 1,3-D (748 plus 140 L/ha) and found that all treatments provided acceptable weed control; however, MS plus CP covered with a plastic tarp for

48 h was the best MS treatment. This treatment controlled grass and broadleaf species equal to MB; however, unacceptable sedge species control was observed. MS applied alone failed to control redroot pigweed (*Amaranthus retroflexus* L.); however, MS plus combinations provided control (Unruh et al. 2002). That was confirmed by Fennimore et al. (2003), who found that MS (42%) was less effective than MB:CP on weed seed control. Among MB, MeI, propargyl bromide, 1,3-D and MS and the combinations of these with CP, MS and propargyl bromide were the most effective in controlling yellow nutsedge (*Cyperus esculentus* L.) (Hutchinson et al. 2003).

The tarp laid immediately after application has an important role in fumigant efficacy. The use of both MS at 468 L/ha and Telone C-17 (1,3-D plus 17% CP) at 126 L/ha provided good pest control and had high plant yield and vigor when covered with a polyethylene film immediately after treatment. The same treatment not covered with polyethylene film but sealed with a mechanical soil cultipacker provided poor control of weeds (Csinos et al. 1997). Application of MS (748 L/ha) followed by CP 99% (168 kg/ha, shank injected) without tarp provided grass control similar to MB, but it was reduced at five weeks after treatment (Unruh et al. 2002). In addition, MS treatments tarped after application improved weed control compared to the same treatment non tarped (Westerdahl et al. 2002).

Dazomet is another pesticide that transforms into MITC. It is used for pre-plant control of weeds, nematodes, and soil diseases in nurseries, greenhouses, turf, and ornamentals. The physical characteristics of dazomet make it difficult to use. It is formulated as a light powder, which is subject to drift. Equipment must be sealed to limit spillage (Unruh et al. 2002). Dazomet and MS are highly dependant on soil preparation

and moisture for activation and uniform distribution of MITC. Inconsistent results are often obtained because of improper methodology (Annis and Waterford 1996).

Treatments with both dazomet 99% (392 kg/ha) and CP 99% (168 kg/ha) or dazomet 99% (392 kg/ha) and 1,3-D 98% (140 L/ha) provided 80% and 51% control of purple nutsedge (*Cyperus rotundus* L.) respectively, but these treatments declined in nutsedge control within 11 months after treatment (Unruh et al. 2002). All dazomet combinations controlled bermudagrass (*Cynodon dactylon* (L.) Pers.) 96 to 100%. Carpetweed (*Mollugo verticillata* L.) was controlled as well as in MB with dazomet plus CP, however the other combinations were not as efficient. The efficacy of dazomet and combinations against winter annual weeds was similar to that of MB (Unruh et al. 2002).

1,3-dichloropropene (1,3-D) is registered as a nematicide. It is not known to have fungi and insects control. High rates, 1,3-D have some efficacy against a few weeds. This fumigant does not deplete the ozone layer and has a short half-life of 7 to 12 hours. (Messenger and Braun 2000). It has restricted usage in California due to residue problems in air samples collected in urban areas adjacent to farms. This product has been listed in California as a carcinogen (Ristaino and Thomas 1997).

1,3-D plus oxadiazon (140 L/ha, 168 kg/ha) did not control yellow nutsedge (*Cyperus esculentus* L.) , purple nutsedge, bermudagrass, or carpetweed, but provided 83% control of the winter annual weed species (Carolina geranium - *Geranium carolinianum* L, cutleaf eveningprimrose - *Oenothera laciniata* Hill, wandering cudweed - *Gamochaeta pensylvanica* (Willd.) Cabrera), 71% control of alexandergrass (*Urochloa plantaginea* (Link) R.D. Webster) and broadleaf signalgrass (*Urochloa platyphylla* (Nash) R.D. Webster), and 80% control of tall morningglory (*Ipomoea purpurea* (L.)

Roth), sharppod morningglory (*Ipomoea cordatotriloba* Dennst.), and redroot pigweed (Unruh et al. 2002). Application of Telone C-17 (1,3-D 83%, CP 17%) resulted in an effective concentration to give 50% mortality for yellow nutsedge control, similar to that of MeI applied alone (Hutchinson et al. 2003). In one location, application of 1,3-D (93 L/ha) followed by MS (349 L/ha) and Telone C-17 (93 L/ha) followed by MS (349 L/ha) controlled oldfield toadflax (*Nuttallanthus canadensis* (L.) D.A.) and purple cudweed (*Gamochaeta purpurea* (L.) Cabrera) as well as MB plus CP standard. Only combination treatments of MS and 1,3-D, CP and 1,3-D were equivalent to MB for control of cutleaf eveningprimrose. In the second location MS, 1,3-D plus CP plus MS and 1,3-D plus MS were not different from MB plus CP standard treatment for control of purple cudweed, oldfield toadflax and corn spurry (*Spergula arvensis* L.). In addition all treatments except CP were equal to MB plus CP standard in weed control for corn spurry, cutleaf eveningprimrose, yellow nutsedge, henbit (*Lamium amplexicaule* L.) and annual sedge (*Cyperus compressus* L.) in the second year experiment (Csinos et al. 2000).

Gilreath et al. (2005) found that MB plus CP consistently controlled *Cyperus* spp. better than the other fumigants; however, most of the MB alternatives that included 1,3-D reduced *Cyperus* spp. populations compared to the non-fumigant control. Napropamide at 4.50 kg/ha, metolachlor at 2.25 kg/ha, and pebulate at 4.5 kg/ha, applied three weeks before planting and incorporated, did not interact with different fumigants applied the same day and had excellent control of goosegrass (*Eleusine indica* L.), southern crabgrass (*Digitaria ciliaris* L.) and smooth pigweed (*Amaranthus hybridus* L.), but only poor to fair control of purple nutsedge (Gilreath et al. 2004). However, the same author concluded in 2005, that 1,3-D (325 kg ai/ha) plus CP (67 kg ai/ha) combined with

pebulate consistently reduced purple nutsedge density more than any other fumigant-herbicide combination during the early stages of the crop at 5 WAT. In addition, improved efficacy was achieved when pebulate was deep incorporated (Gilreath and Santos 2005). This result is consistent with the research done by the same author the year before where high doses and deep incorporation of napropamide and metolachlor provided the best weed control; Telone C-17 had some purple nutsedge control but still was insufficient to achieve maximum yield (Gilreath and Santos 2004). Efficacy of 1,3-D plus CP (60%, 32%) and CP EC on seed control in little mallow (*Malva parviflora* L.) or prostrate knotweed (*Polygonum aviculare* L.) did not differ from MB:CP (67:33) (Fennimore et al. 2003).

Chloropicrin (CP) may be used to control nematodes, bacteria, fungi, insects, and weeds. CP has been shown to be very effective as a fungicide when compared to MB (Messenger and Braun 2000). CP has marginal activity against some nematodes and weeds (Ristaino and Thomas 1997); for this reason CP is combined extensively with MB, and more recently with 1,3-D (Unruh et al. 2002). Increased concentration and time exposure with CP reduced common chickweed (*Stellaria media* (L.) Vill.), common purslane (*Portulaca oleracea* L.), and prostrate knotweed seed viability. This was confirmed with a field experiment (Haar et al. 2003). CP at 224 kg/ha provided consistently equivalent weed control to MB 67% plus CP 33% at 392 kg/ha in common chickweed, little mallow, common purslane, and prostrate knotweed (Kabir et al. 2004). CP does not degrade the ozone layer, but it is a potential groundwater contaminant (Messenger and Braun 2000).

Weed seed population is an important aspect to consider in weed control management to reduce weed population in succeeding years. Laboratory studies showed that CP concentration and time of exposure have a direct relationship with seed viability. Higher concentration and longer exposure resulted in reduced percentages of viable seeds of common chickweed, common purslane and prostrate knotweed. Field studies with CP applied at 83, 110, 138, 165 and 220 kg/ha supported this conclusion, but seeds of little mallow and redstem filaree (*Erodium cicutarium* (L.) L'Hér. ex Ait.) were not affected (Haar et al. 2003).

Iodomethane (MeI) is chemically analogous to MB and it is not currently registered. MeI is destroyed rapidly in the troposphere with about one week of atmospheric life (Ristaino and Thomas 1997). Research done with MeI confirmed that it is a strong candidate to replace MB. MeI is a better methylating agent than MB; it is rapidly destroyed by UV light and therefore unlikely to be involved in stratospheric ozone depletion. In laboratory and field studies MeI was equal to or better than MB in controlling soilborne pathogens and weeds (Ohr et al. 1996). It is thought that the price of MeI will be significantly more expensive than MB. However, the current MeI price could decrease in response to higher production and increased demand from agricultural uses (Hueth et al. 2000).

MeI controlled grasses, sedges, and broadleaf weeds present at two locations under different environmental conditions, but did not control redroot pigweed (Unruh et al. 2002). Zhang et al. (1997), however, found that redroot pigweed was the most sensitive and yellow nutsedge was the least sensitive to MeI. Furthermore, MeI was as potent as MB for redroot pigweed but more potent than MB for annual ryegrass (*L. multiflorum*

Lam.), velvetleaf (*Abutilon theophrasti* Medik.), common lambsquarters (*Chenopodium album* L.), common purslane, wild mustard (*Brassica kaber* (DC.) L.C. Wheeler), yellow nutsedge and purple nutsedge. Under field conditions, MeI at 280 kg/ha killed all species tested except eastern black nightshade, *Solanum ptychanthum* Dunal (Zhang et al. 1997). MeI controlled velvetleaf and annual ryegrass in different soil moisture, temperature, and soil texture. The optimal soil moisture to control those weeds was 14% water content (W/W) and the results were obtained with temperatures above 20 C. Time to 100% mortality of weeds was 24 h for MeI fumigation and 36 h for MB when 200 mole of fumigant was used (Zhang et al. 1998).

Propargyl bromide (PB) half-life in soil ranged from 1.2 to 5 days, depending on the soil type. Under typical agricultural soil conditions, it diffuses readily, a desirable characteristic for fumigants. Due to its short degradation time in soil, PB should not pose a serious environmental risk (Yates and Jianying 1998). The concentration of PB required to control 50% of barnyardgrass (*Echinochloa crus-galli*) seeds was 18 fold higher for muck soil compared to sandy loam and loamy sand soils. The low efficacy in muck soil was a result of rapid degradation and high adsorption of the compound in the soil. Propargyl bromide's half-life was 7 hours in muck soil, compared to 60 and 67 hours in sandy loam and loamy sand, respectively (Ma et al. 2001). Degradation rate of propargyl bromide increased with increasing soil organic matter content and the degradation coefficient (k) value was correlated to the organic carbon content (Papiernik et al. 2002). Propargyl bromide and MS were the most efficacious fumigants tested in controlling yellow nutsedge tubers. MB, MeI, PB, 1,3-D and MS applied with 17% CP resulted in a

synergistic interaction; MB had more benefit and PB had the least benefit with this combination (Hutchinson et al. 2003).

Propylene oxide (PPO) is currently registered for post harvest application and industrial uses. The Environmental Protection Agency (EPA) has classified propylene oxide as a Group B2, probable human carcinogen (Anonymous 2005). Combination treatments of PPO plus MS resulted in superior weed control compared with PPO or MS alone, indicating a synergy between these compounds (Rodriguez-Kabana and Simmons 2004). PPO controlled germination of morningglory (*Ipomoea spp.*) seed at rates higher than 406 kg ai/ha and yellow nutsedge germination was inhibited at all rates evaluated (227 to 912 kg ai/ha) (Belcher et al. 2004).

Sodium azide is a highly-effective, broad-spectrum fumigant that controls soil-borne weeds, nematodes, fungi, and bacteria (Richards 2004). Effective weed control was obtained with rates higher than 85 kg ai/ha. Sodium azide at 57 and 84 kg ai/ha controlled root diseases and weeds similarly to MB (Rodriguez-Kabana et al. 2004). Weed control by sodium azide at 112 kg ai/ha was as effective as MB at one experiment location (Oxnard) but not in the other (Watsonville), but when combined with CP was equivalent to MB in both locations (Kabir et al. 2004).

InLine (1,3-D 61% plus CP 33%) at 236 and 393 L/ha, CP (95%) at 130 and 200 L/ha, and Vapam (MS 42%) at 420 and 700 L/ha applied by drip irrigation systems provided equal or better weed control than equivalent rates applied by shank injection (Fennimore et al. 2003). There was no nutsedge control where Telone C-35 (1,3-D 65% plus CP 35%) was applied broadcast, but when applied in-bed or broadcast followed by in-bed application of CP, nutsedge control was comparable to MB (Gilreath et al. 2002).

Alternative fumigants, MeI plus CP, Telone II, Telone C35 with high density polyethylene, and Telone C35 with a virtually impermeable film were as effective as MB in reducing seed viability of field bindweed (*Convolvulus arvensis* L.), annual morningglory, johnsongrass (*Sorghum halepense* L.), and common purslane. However, none of the treatments reduced seed viability of little mallow. In addition, alternative treatments required similar amounts of hand weeding as MB treatment (Shrestha et al. 2004).

Economic impact of the MB phaseout was evaluated by other authors. Hueth et al. (2000) analyzed the economic aspect of MB being replaced by MeI, which is a strong candidate to replace MB from a technical point of view. Sources of raw material, product cost, and supply-demand analysis is presented. Even though the economic aspect and the cost analysis play an important role in defining which product or production management will be adopted, this point is beyond our scope, and it is not covered in this research.

Alternative methods can be utilized to reduce agricultural fumigant emissions into the atmosphere. Papiernik et al., (2004) applied 1,3-dichloropropene (1,3-D), MS, and propargyl bromide to soil beds via drip irrigation at 15 cm depth and found that cumulative emissions of MITC and 1,3-D were decreased approximately 80% from the soil by tarping the bed with virtually impermeable film (VIF) rather than high-density polyethylene (HDPE). In addition, tarping the bed with 1-mil (HDPE) or (VIF) resulted in a more effective fumigant vapor containment (Haar et al. 2003). Another way to reduce fumigant emissions is by chemical reaction; MeI not only is weakly sorbed, but also is highly mobile in Salinas clay loam and Arlington sandy loam soils (Park et al.

2004). Emissions of this gas, however, can be controlled by spraying thiourea on the soil, thus reducing the half-life of MeI from 300 hours to a few hours (Zheng et al. 2004).

Other weed control methods: Non-chemical

There are non-chemical alternatives to MB. For instance, soil may be treated with steam, which controls most soil-borne pathogens and weeds. There are several systems for applying steam to soil. However, the use of steam as a soil sterilant is limited by the expense of application, and by the difficulty of use. It can be utilized successfully in some situations such as high value crops or in a special disease control program (Messenger and Braun 2000).

Soil solarization is the process of raising soil temperature by tarping the soil during the warm season. The heat created by visible light converted to infrared energy that can not pass through the tarp raises the temperature and kills organisms in the soil. Yields of strawberry in solarized soil were similar to those of MB treated soil (Rieger et al. 2001). This method is compatible with other physical, chemical, and biological methods (Messenger and Braun 2000). Common purslane, tumble pigweed (*Amaranthus albus* L.), and black nightshade seeds were susceptible to temperatures above the threshold temperature of 60 C using double-tent solarization. Soils in small containers reached higher temperatures and were maintained at high temperature (above 60 C) for a longer period of time, than soil in larger containers. This technique can be used by commercial growers to effectively and inexpensively produce weed-free soil and potting mixes in warmer climate areas (Stapleton et al. 2002). Arbuscular mycorrhiza fungi were not reduced immediately after solarization but were reduced eight months after

application. Solarization apparently reduces arbuscular mycorrhiza fungi by reducing the weed population that maintained infective propagules over the winter (Schreiner et al. 2001).

Crop rotation can decrease pathogen inoculum in soil by alternating resistant crop and susceptible crops. The drawback is the time needed to be effective and the crop is often rotated with non-cash crops contributing little to farm income (Messenger and Braun 2000). Biological control can be used as a part of an integrated pest management program to target specific pathogens and pests (Ristaino and Thomas 1997). Relatively little research on cover crops has been conducted on ornamental crops compared to corn, soybean, and horticultural produce. Cover crops can suppress weeds through competition for light and nutrients or allelopathy (Messenger and Braun 2000).

Cover crop and management system combinations are capable of decreasing weed pressure. Brassicaceae cover crops also can exert a weed-suppressive effect through the release of isothiocyanates from glucosinolates after decomposition of plant tissues (Angelini et al. 1998). This effect, which also can reduce soil borne pathogens and nematodes, is often referred to as bio-fumigation (Kirkegaard and Matthiessen 2004; Melander et al. 2005)

Although integrated pest management is a valid option in controlling pests, chemical pesticides represent the most common currently used tool for pest control. Large numbers of pests can attack a large number of species making it difficult for growers to reduce the amount of pesticides applied. Since crop appearance is important in the ornamental industry, preventative pesticide applications are heavily used (Tatum and Thompson 1993). Biological weed control has not been used due to the diversity of

weeds present in nurseries and the specificity of biological control in weeds (Knox et al. 2003).

Other weed control methods: Herbicides

Technology such as combinatorial chemistry developed in the last decade, allows the production of thousands of chemicals, creating libraries of information about new molecules; these molecules can not only be tested for pharmaceutical purposes but also for herbicide activity with “high throughput screens”, which test for herbicide activity. However, in the last decade fewer new herbicidal molecules have been released in the market. Companies are reluctant to release a new compound into the market because they have to compete with glyphosate, a product that is widely known and accepted and it is a very cost effective herbicide (Penner 2005).

Herbicide selectivity on crops depends on a wide range of factors and the complex interactions between them. Herbicide characteristics such as absorption, formulation, mode of action, translocation, herbicide placement, and plant factors like stage of growth, growing point location, leaf properties, and metabolism are important factors that determine herbicide selectivity. Weed control by cultivation can potentially damage herbaceous perennial species because storage organs are located just below ground and shallow roots are common. Herbicides can reduce weed control costs; however, little information about herbaceous perennial tolerances to herbicides is available and few herbicides are labeled for use in this production system (Calkins et al. 1996).

Tolerance of herbaceous perennials to pre and post emergent herbicides is highly dependent on species (Calkins et al. 1996; Derr and Salihu 1996). Response to isoxaben was different when applied to dwarf burning bush (*Euonymus alatus* (Thunb) Sieb. 'Compacta') foliage and in wintercreeper (*Euonymus fortunei* (Turcz.) Hand. Mazz. 'Colorata') even though they share the same genus (Salihu et al. 1999). Reductions in quality were often associated with reduction in size. Furthermore, herbicide injury was greater in younger plants compared to established plants, and also injury was greater in those plants actively growing compared to the dormant plants (Calkins et al. 1996; Salihu et al. 1998).

Herbicide crop selectivity is influenced by crop growth stage. More terbacil was absorbed and translocated to the leaves of field violet with 3 leaves, than field violet with 12 leaves. In addition, most ¹⁴C in roots (77%) and foliage (57%) in the 12 leaf plants was in polar metabolites. These characteristics make the plants with 3 leaves susceptible to terbacil, while plants with 12 leaves are tolerant to the herbicide (Rogers et al. 2001).

Regardless of herbicide toxicity, timing of application was important in injury occurrence. Preemergence applications were sometimes more toxic than postemergence because some buds were initiated prior to the preemergent herbicide application, thus causing injury. For this reason it may be better to apply preemergent herbicides in the fall when plants are dormant (Calkins et al. 1996).

A safener is a substance that reduces toxicity of herbicides to crop plants by physiological mechanisms (Weed Science Society of America 2002). One of seven corn hybrids exhibited an increase in tolerance when the safener, isoxadifen-ethyl, was applied with foramsulfuron (Bunting et al. 2004). Rogers et al. (2001) investigating terbacil

metabolism in strawberry plants, concluded that fluazifop-P inhibited detoxification of terbacil by strawberry.

Injury potential can be affected by herbicide formulation. The wettable powder and emulsifiable concentrate formulations of oxadiazon caused greater injury than the granular formulation to 'Compacta' Japanese holly and 'Hershey Red' azalea 30 days after treatment (Derr and Salihu 1996). Briggs and Whitwell (2002) found that prodiamine granular formulation caused greater injury to sensitive taxa compared to wettable granule and suspension concentrates. Even herbicides with the same active ingredient but different formulations can differ in crop injury. Different injury rates were observed in white spruce (*Picea glauca* (Moench) Voss.) trees treated over the top with three different formulations of glyphosate (Mihajlovich et al. 2004).

Mulches treated with different pre-emergent herbicides can prolong herbicide activity. Oxyfluorfen, oryzalin, and isoxaben applied to different mulches provided excellent weed control. Bark treated with oryzalin had significantly greater efficacy than bark treated with oxyfluorfen or isoxaben. Furthermore, Douglas fir bark treated with oryzalin provided increased efficacy and extended efficacy versus untreated Douglas fir bark or oryzalin alone (Mathers and Case 2002).

Terbacil belongs to the uracil chemical family. This herbicide inhibits photosynthesis by binding to the Q_b -binding niche on the D1 protein of the photosynthesis II complex. Terbacil controls many annual broadleaf and grass weeds including common chickweed, henbit, common lambsquarter, tansymustard, prickly lettuce, crabgrass spp., downy brome, foxtail spp., ryegrass, and barnyardgrass, with partial control of nutsedge (Weed Science Society of America 2002).

Imazapic, imazaquin, and halosulfuron are herbicides that block acetolactate synthase (ALS). The first two belong to the imidazolinone family, while halosulfuron belongs to the sulfonyleurea chemical group. These herbicides inhibit acetolactate synthase (ALS), a key enzyme in the biosynthesis of the branched-chain amino acids isoleucine, leucine, and valine. Imazapic and imazaquin control many annual broadleaf weeds such as pigweed spp., common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters and many annual and perennial grasses including panicum (*Panicum* spp.), johnsongrass, goosegrass, foxtail spp. (*Setaria* spp.), crabgrass (*Digitaria* spp.), and purple and yellow nutsedge. Injury symptoms in plants include growth inhibition, chlorosis of meristematic areas, and general chlorosis and necrosis (Weed Science Society of America 2002). Imidazolinone herbicides are anionic at higher pH, thus more herbicide was found in soil solution at higher pH. The increase in adsorption at lower pH could be the cause of the slower degradation observed at pH 5. Average imazaquin half life is 8 weeks (Weed Science Society of America 2002). However, Aichele et al. (2005) estimated imazaquin half-life at 191 weeks.

Halosulfuron controls velvetleaf, cocklebur (*Xanthium* spp.), and numerous other broadleaves, as well as *Cyperus* species (nutsedge). Rapid growth inhibition and chlorosis are the main symptoms. Halosulfuron applied preemergence does not inhibit seed germination, but as soon weeds emerge chlorosis and necrosis is observed. Halosulfuron has a short to moderate persistence in the soil of about one to two weeks (Weed Science Society of America 2002).

Flumioxazin belongs to the N-phenylphthalimide chemical family, is used pre-emergent, and controls broadleaf weeds such as common ragweed, common

lambsquarters, velvetleaf, pigweed, and black nightshade (*Solanum nigrum* L.). The mode of action is believed to be inhibition of protoporphyrinogen oxidase, an enzyme important in the synthesis of chlorophyll; porphyrins accumulate in susceptible plants causing photosensibilization, which leads to membrane peroxidation. Plants emerging from treated soil become necrotic and die shortly after sunlight exposure (Weed Science Society of America 2002). Flumioxazin affected photosynthesis, as indicated by a reduction in foliar chlorophyll and carotenoid contents, gas exchanges and alteration in plastid structure. As a result plant growth was strongly inhibited (Saladin et al. 2003). Among the selective herbicides applied immediate postemergence to strawberry transplants, flumioxazin and napropamide provided the most consistent control of bur clover (*Medicago polymorpha*) and shepherd's purse (*Capsella bursa-pastoris*) (Manning and Fennimore 2001). Hydrolysis and photolytic degradation rate increased with the pH increase, and the degradation products formed by photolysis were the same as those formed by hydrolysis (Kwon et al. 2004).

Isoxaben belongs to the benzamide chemical family. Isoxaben can be applied in established turf, ornamentals, nursery stock, non-bearing fruit trees, and Christmas tree plantations. Isoxaben controls common chickweed, clover spp., dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), henbit, prostrate knotweed, plantain spp (*Plantago* spp), and many other annual broadleaf weeds. If applied preemergence, susceptible weeds fail to emerge. Isoxaben inhibits cell wall biosynthesis. Broadleaf weeds show stunting, reduced root growth, root hair distortion, and root clubbing (swelling of meristematic and elongation zones), symptoms similar to those caused by dinitroaniline herbicides. Isoxaben persistence in soil is moderate to long, with a half life of 2 to 4

months in field conditions; weed control extends to 6 months (Weed Science Society of America 2002).

Trifluralin belongs to the dinitroaniline chemical family. It is labeled for more than 80 crops. It is used on nursery stock, ornamental shrubs, groundcovers and established flowers. Trifluralin controls annual grasses and some small-seeded broadleaf weeds. This herbicide binds to tubulin, the major microtubule protein, resulting in absence of the spindle apparatus, thus preventing alignment and separation of chromosomes. Susceptible weeds fail to emerge, due to inhibition of coleoptile growth or hypocotyls unhooking. Roots appear stubby with thickened tips. The average life time in soil is 45 days for most soils, but depends on the temperature. Residues can persist to the following year with the possibility of crop injury, especially on small grains and corn (Weed Science Society of America 2002). Trifluralin was one of the highest volatile flux losses with 14.1% compared to metolachlor, and atrazine (Rice et al. 2002).

Hypothesis / Plan of research

Research on MB alternatives has been conducted with strawberries, tomatoes, peppers, tobacco, and cucumber in California where MB is heavily used, but relatively little amount has been done in ornamentals and conifers. Furthermore, this information is not applicable to Michigan because of different environmental conditions and these results cannot be directly extrapolated to ornamental plants. Thus, MB research is needed in Michigan to improve our knowledge about alternative products that can replace MB in the ornamental industry in order to reduce the impact of MB phase out.

One of the primary reasons growers apply soil fumigants in nurseries and greenhouses is weed control. In addition, as Calkins (1996) and Derr (1996) stated, herbaceous perennial tolerance to herbicides is highly dependent on species. Thus, knowledge about herbicide efficiency and ornamental crop tolerances will influence weed management decisions, thus increasing the range of herbicide uses for weed control and reducing the amount of fumigant applied to the field.

Two approaches have been proposed to find alternatives to MB. The first is to find similar broad spectrum fumigants as MB that have potential to replace it and do not have a negative effect on the ozone layer. Second, find products that specifically control certain pests and by adding these effects we achieve a broad spectrum as with MB. In our case we evaluate herbicides that can replace MB for weed control.

The objectives are, 1) evaluate the effects of broad spectrum and ozone-harmless fumigants on weed control and crop response, 2) evaluate herbicides for weed control, and herbaceous perennials and conifers response to those herbicides, and 3) evaluate the efficacy of selected herbicides on selected noxious weeds.

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Table 1. Common weeds of nursery crop products.

Perennial weeds	Summer weeds	Winter weeds
<i>Cynodon dactylon</i>	<i>Pilea microphylla</i>	<i>Cardamine spp.</i>
<i>Stachys floridana</i>	<i>Molluga verticillata</i>	<i>Daucus carota</i>
<i>Convolvulus arvensis</i>	<i>Digitaria sp.</i>	<i>Phyllanthus urinaria</i>
<i>Cerastium vulgatum</i>	<i>Fatoua villosa</i>	<i>Stellaria media</i>
<i>Eupatorium capillifolium</i>	<i>Commelina diffusa</i>	<i>Trifolium repens</i>
<i>Smilax spp.</i>	<i>Hydrocotyle spp.</i>	<i>Gnaphalium spp.</i>
<i>Senecio vulgaris</i>	<i>Eclipta sp.</i>	<i>Geranium carolinianum</i>
<i>Sorghum halepense</i>	<i>Oenothera spp.</i>	<i>Anthem cotula</i>
<i>Pueraria Montana var. lobata</i>	<i>Elusine indica</i>	<i>Medicago trunculata</i>
<i>Marchantia polymorpha</i>	<i>Chenopodium spp.</i>	<i>Medicago lapolina</i>
<i>Ipomoea spp.</i>	<i>Ipomoea spp.</i>	<i>Brassica spp.</i>
<i>Cyperus rotundus</i>	<i>Fatoua villosa</i>	<i>Lepidium spp.</i>
<i>Cyperus esculentus</i>	<i>Phyllanthus urinaria</i>	<i>Lotium multiflorum</i>
<i>Toxicodendron aradicans</i>	<i>Phyllanthus tenellus</i>	<i>Capsella bursa-pastoris</i>
<i>Rosa multiflora</i>	<i>Amaranthus spp.</i>	<i>Sonchus spp.</i>
<i>Panicum repens</i>	<i>Portulaca oleracea</i>	<i>Vicia sativa</i>
<i>Campsis radicans</i>	<i>Richardia scabra</i>	
	<i>Ambrosia artemisiifolia</i>	
	<i>Cyperus compressus</i>	
	<i>Cyperus globulosus</i>	
	<i>Bidens bipinnata</i>	
	<i>Chamaesyce hirta, syn. Euphorbia hirta</i>	
	<i>Chamaesyce hirta, syn. Euphorbia vermiculata</i>	
	<i>Chamaesyce hirta, syn. Euphorbia humistrata</i>	
	<i>C. maculate, syn. E. maculate, E. supine</i>	
	<i>Oxalis stricta</i>	

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Table 2. Properties of soil fumigants.

Comon name	Trade name	Formulation	Status	Pest control activity
Methyl Bromide	Brom-o-Gas	MB 98% + CP 2%	Registered	Nematodes, weeds, fungi, insects
Methyl Bromide	Terro-gas-67	MB 67% + CP 33%	Registered	Nematodes, weeds, fungi, insects
Metham sodium	Vapam	Sodium methylidithiocarbamate 42% + 58% inerts	Registered	Nematodes, weeds, fungi, insects
Chloropicrin	Chloropicrin	Chloropicrin 99.5%	Registered	Nematodes, fungi, insects
1,3-D	Telone II	1,3-Dichloropropene 97.5%	Registered	Nematodes, fungi, insects
1,3-D	Telone C-35	1,3-Dichloropropene 65% + 35% CP	Registered	Nematodes, fungi, insects
1,3-D	Telone C-17	1,3-Dichloropropene 83% + 17% CP	Registered	Nematodes, fungi, insects
1,3-D	Telone EC	1,3-Dichloropropene 93.6 %	Registered	Nematodes, fungi, insects
Dazomet	Basamid	Dazomet granular 99%	Registered	Nematodes, weeds, fungi, insects
Methyl iodide	Methyl iodide	MeI 98% + CP 2%	Not registered	Nematodes, weeds, fungi
Methyl iodide	Methyl iodide	MeI 50% + CP 50%	Not registered	Nematodes, weeds, fungi
Propylene oxide	Propozone	Propylene oxide 100%	Not registered	Nematodes, fungi
Propargyl bromide	INA	INA	Not registered	INA
Sodium azide	Sep-100	INA	Not registered	Nematodes, weeds, fungi

INA: information not available

CHAPTER III: COMPARATIVE EVALUATION OF SOIL FUMIGANTS

INTRODUCTION

Fumigants are used to control soil-borne pests, which allows high yields production of superior quality products, which are important in order to be competitive in a high value crop market (Messenger and Braun 2000). Methyl bromide (MB) is the most widely used fumigant, with 68,424 metric tons used in 1996, almost half of which was in the USA (Ware 2000). MB diffuses quickly and penetrates deeply into the soil due to its low boiling point and high vapor pressure. It has a short waiting period before planting, and low residual phototoxicity (Messenger and Braun 2000).

MB research has been conducted extensively in high value crops such as strawberries, tomatoes, peppers, tobacco, and cucumbers. On the other hand, there has been limited research for MB alternatives in the ornamental and conifer industries in Michigan, even though this state is one of the six largest nursery and floriculture producers, with sales of \$629 million in 2002 (Anonymous 2002). Nursery and greenhouse production represent the sixth largest agricultural commodity group in the United States. This is the fastest growing segment of the U.S. agriculture; between 1991 and 1998 sales of this segment increased 30%. Nursery growth is driven by the strong U.S. economy with the expansion in housing and increase of ornamental plant consumption (Knox et al. 2003).

In addition to MB, nursery operators use other weed control practices, such as mulches, plant density, and mechanical removal, but chemical methods remain the most used weed control method in nurseries (Anonymous 2004a).

MB has been used since before World War II. The total amount used has increased steadily with a 60% increase between 1984 and 1992 (Price 1996). MB is a

fumigant that is injected into soil before planting to control fungi, weeds, pathogens, and nematodes. The United States utilizes about 27 million kilograms each year: approximately 75% on soil before planting crops, 11% in harvested commodities during storage and export, and 6% in structures such as food processing plants, warehouses, and museums, as well as transport vehicles. The remaining 8% goes to the production of other chemicals (Anonymous 2004b). Globally, the usage percentage follows the same patterns (Ware 2000).

Manufactured MB is a colorless gas at temperatures above 3.5 C and at low concentrations has no noticeable odor. Chloropicrin at 2% is added as a warning gas. Reactions with organic and living materials are not highly specific, making mode of action determination quite difficult. In fact, the mode of action is not very well understood. Methylation of sulfhydryl groups and the following enzyme inactivation has been postulated to play an important role in its toxicity. MB is highly soluble in lipids and has a high toxicity; it is lethal to rabbits at oral dosages above 60 mg kg⁻¹ (Price 1996).

Atmospheric MB originates from oceanic emissions and anthropogenic sources such as biomass burning, agricultural applications, leaded gasoline combustion, and structural fumigations. The relative contributions of anthropogenic and natural emissions to the total atmospheric MB are not well known (Butler and Rodriguez 1996). However, it was estimated that man-made sources account for 35% and natural sources account for 65% (Hanwant 1993). According to Mano et al.(1994), biomass burning represents a major contribution of bromine in the stratosphere and can be compared to the amount produced by ocean emissions and pesticides.

Methylation of soil organic matter may be the major pathway for degradation of MB (Tao and Maciel 2002). According to the USDA 2004 Annual Report (2004b) hydrolysis is the major transformation pathway for fumigants and soil pH, soil moisture, and organic content can accelerate degradation. Even though fumigants are potent biocides, bacteria can be involved in MB degradation by directly oxidizing it during field fumigation (Miller et al. 1997).

The Montreal Protocol defined MB as a chemical that contributes to depletion of the Earth's ozone layer. Thus, manufacture and importation of MB will be limited until completely phased out in developed countries for general agricultural uses in 2005, and developing countries have agreed to eliminate most chlorofluorocarbon (CFC) by January 2010 (Anonymous 2004c).

Many industries will be affected by the loss of MB. The ornamental and nursery industry in California is estimated to lose \$129 million and \$14 million in North Carolina (Carpenter 2000). Even though current application cost is approximately \$ 4,000 per hectare, the ornamental industry still relies on this product to achieve maximum yield and quality. Michigan used 220 metric tons of MB in 2000. The target objective of MB application nematodes, weeds, and fungi (Bird 2004). In the turf industry, MB fumigation is primarily used to eliminate weeds and to ensure genetic purity of turf grasses (Unruh et al. 2002).

The MB phase out will adversely affect agricultural production, especially where alternative fumigants have not been thoroughly evaluated. At the moment there are few fumigants that can readily substitute for MB. According to Duniway (2002), "None of the chemical alternatives currently registered and available have the full spectrum of activity

and versatility of MB as a pre-plant soil fumigant. Methyl iodide and propargyl bromide probably have activity that most closely parallels that of MB in soil". Studies confirm that no EPA-registered fumigant alternative to MB, applied alone or in combination for pre plant turf soil fumigation, exists (Unruh et al. 2002).

Some of the fumigants proposed to replace MB are: metham sodium (MS), chloropicrin (CP), 1,3-dichloropropene (1,3-D), dazomet, and methyl iodide (MeI). Fumigants that may not deplete the ozone layer and have potential to replace MB are listed in table 1.

MS and dazomet are used to control soil fungi, insects, nematodes and weeds. They decompose in soil to methyl isothiocyanate (MITC) which is the biocidal molecule. Dazomet and MS are highly dependant on soil preparation and moisture for activation and uniform distribution of MITC, thus inconsistent results are often obtained (Annis and Waterford 1996).

MS was one of the most efficacious fumigants tested in controlling yellow nutsedge (*Cyperus esculentus* L) tubers. MS applied with 17% CP resulted in a synergistic interaction (Hutchinson et al. 2003).

MS (748 L/ha) alone and MS (748 L/ha) followed by CP (168 kg/ha), tarped and not tarped, and MS (748 L/ha) followed by 1,3-D (140 L/ha) provided acceptable weed control; however, MS plus CP covered with a plastic tarp after treatment for 48 h was the best MS treatment controlling grass and broadleaf species equal to MB, but unacceptable sedge species control. MS applied alone failed to control redroot pigweed (*Amaranthus retroflexus* L.); however, MS plus combinations provided control (Unruh et al. 2002). That was confirmed by Fennimore et al.(2003), who found that MS was less effective

than MB:CP for weed seed control. Among MB, MeI, propargyl bromide, 1,3-D and MS and the combinations of these with CP, MS and propargyl bromide were the most effective in controlling yellow nutsedge (Hutchinson et al. 2003).

Treatments with both dazomet 99% (392 kg/ha) and CP 99% (168 kg/ha) or dazomet 99% (392 kg/ha) and 1,3-D 98% (140 L/ha) provided 80% and 51% control of purple nutsedge respectively, but these combinations declined in nutsedge control 44 weeks after treatment. All dazomet combinations controlled 96 to 100% of bermudagrass. Carpetweed was controlled as well as in MB with dazomet (392 kg/ha) followed by CP (168 kg/ha), however the other combinations were not as effective. The efficacy of dazomet and combinations against winter annual weeds was similar to that of MB (Unruh et al. 2002).

1,3-D is registered as a nematicide. 1,3-D has restricted usage in California due to residue problems in air samples collected in urban areas adjacent to farms. It is listed in California as a carcinogen (Ristaino and Thomas 1997).

1,3-D shank injected at 140 L/ha followed by oxadiazon 2% granular at 168 kg/ha broadcast applied did not control yellow nutsedge, purple nutsedge (*Cyperus rotundus* L.), or coastal bermudagrass (*Cynodon dactylon* (L.) Pers.) and carpetweed (*Mollugo verticillata* L.), but provided 83% control of the winter annual weed species (Unruh et al. 2002). Combining 1,3-D (Telone II) with 17% CP resulted in an EC₅₀ value for yellow nutsedge control similar to that of MeI applied alone (Hutchinson et al. 2003).

Application of 1,3-D (93 L/ha) followed by MS (349 L/ha) and Telone C-17 (93 L/ha) followed by MS (349 L/ha) controlled oldfield toadflax (*Nuttallanthus canadensis* (L.) D.A.), corn spurry (*Spergula arvensis* L.), evening primrose (*Oenothera laciniata* Hill),

yellow nutsedge, henbit (*Lamium amplexicaule* L.), annual sedge (*Cyperus compressus* L.), and purple cudweed (*Gamochaeta purpurea* (L.) Cabrera) as well as MB plus CP standard. On the other hand, CP was the least effective (Csinos et al. 2000).

1,3-D plus CP (83:17) at 330 L/ha combined with napropamide at 4.50 kg/ha, metolachlor at 2.25 kg/ha, pebulate at 4.50 kg/ha did not interact with the fumigants and had excellent control of goosegrass (*Eleusine indica* L.), southern crabgrass (*Digitaria ciliaris* L.) and smooth pigweed (*Amaranthus hybridus* L.), but only poor to fair control of purple nutsedge (*Cyperus rotundus* L.) (Gilreath et al. 2004). However, the same author concluded in 2005, that 1,3-D (325 kg ai/ha) plus CP (67 kg ai/ha) combined with pebulate consistently reduced purple nutsedge density more than any other fumigant-herbicide combination during the early stages of tomato at 5 WAT. In addition, improved efficacy was achieved when pebulate was deeply incorporated (Gilreath and Santos 2005). This result is consistent with the research done in tomato and pepper by the same author the year before where high doses and deep incorporation of napropamide and metolachlor provided the best weed control; Telone C-17 (1,3-D 83%) reduced purple nutsedge density but still was not enough to achieve maximum yield (Gilreath and Santos 2004). Efficacy of InLine (1,3-D 60% plus CP 32%) and CP EC 95% applied through drip irrigation system on seed control in little mallow (*Malva parviflora* L.) or prostrate knotweed (*Polygonum aviculare* L.) did not differ from MB:CP (67:33) (Fennimore et al. 2003).

CP may be used to control nematodes, bacteria, fungi, insects, and weeds. CP has marginal activity against nematodes and weeds (Ristaino and Thomas 1997), furthermore, CP alone provided poor weed control (Csinos et al. 2000); for this reason

CP is combined extensively with MB, and more recently with 1,3-D (Unruh et al. 2002). Laboratory studies found that increased concentration and exposure time with CP reduced common chickweed (*Stellaria media* (L.) Vill.), common purslane (*Portulaca oleracea* L.), and prostrate knotweed (*Polygonum aviculare* L.) seed viability. This was confirmed with a field experiment (Haar et al. 2003). CP at 224 kg/ha provided equivalent weed control to MB 67% plus CP 33% at 392 kg/ha in common chickweed, little malow, common purslane, and prostate knotweed (Kabir et al. 2004). Even though CP does not degrade the ozone layer, it is a potential groundwater contaminant (Messenger and Braun 2000).

MeI is chemically analogous to MB and it is not currently registered. Research with MeI combined with CP confirmed that it is a strong candidate to replace MB. MeI is a better methylating agent than MB; it is rapidly destroyed by UV light and therefore unlikely to be involved in stratospheric ozone depletion. In laboratory and field studies MeI was equal to or better than MB in controlling soil borne pathogens and weeds (Ohr et al. 1996). MeI is an expensive chemical, however MeI current price could change dramatically in response to increased demand from agriculture uses (Hueth et al. 2000).

MeI controlled grass species, sedge species, and broadleaf weeds present at the two locations under different environmental conditions, but did not control redroot pigweed (Unruh et al. 2002). Zhang et al. (1997) found that redroot pigweed was the most sensitive and purple nutsedge was the least sensitive to MeI. Furthermore, MeI was as potent as MB for redroot pigweed but more potent than MB for annual ryegrass (*L. multiflorum* Lam.), velvetleaf (*Abutilon theophrasti* Medik.), common lambsquarters (*Chenopodium album* L.), common purslane, wild mustard (*Brassica kaber* (DC.) L.C.

Wheeler), yellow nutsedge and purple nutsedge. Under field conditions, MeI at 280 kg/ha killed all species tested except black nightshade (*Solanum nigrum* L.) (Zhang et al. 1997). MeI controlled velvetleaf and annual ryegrass in different soil moisture, temperature, and soil texture. The optimal soil moisture to control those weeds was 14% water content (W/W) and the results were obtained with temperatures above 20 C. Time to 100% mortality of weeds was 24 h for MeI fumigation and 36 h for MB, indicating MeI is more effective on a molar basis (Zhang et al. 1998).

Propargyl bromide half-life in soil ranged from 1.2 to 5 days, depending on the soil type, and it should not pose a serious environmental risk (Yates and Jianying 1998). Propargyl bromide weed control efficacy is reduced greatly in muck soil due to its rapid degradation and high adsorption of the compound in the soil. Propargyl bromide half-life was only 7 hours in the muck soil compared to 60 and 67 hours in the sandy loam and loamy sand, respectively (Ma et al. 2001).

Propylene oxide (PPO) is currently registered for post harvest uses. PPO is used in the production of polyethers (the primary component of polyurethane foams) and propylene glycol and in the fumigation of foodstuffs and plastic medical instruments and in the manufacture of dipropylene glycol and glycol ethers, as herbicides, as solvents, and in the preparation of lubricants, surfactants, and oil emulsifiers. Environmental Protection Agency (EPA) has classified propylene oxide as a Group B2, probable human carcinogen (Anonymous 2005). PPO combined with MS resulted in superior weed control compared with PPO or MS alone, this indicates a high synergy between these compounds (Rodriguez-Kabana and Simmons 2004). PPO controlled germination of morning glory

(*Ipomoea spp.*) seed at rates higher than 406 kg ai/ha and yellow nutsedge germination was inhibited in all rates (227 to 912 kg ai/ha) (Belcher et al. 2004).

Sodium azide formulated as SEP 100, has proven to be a highly-effective, broad-spectrum pesticide that controls soil-borne weeds, nematodes, fungus and bacteria (Richards 2004). Effective weed control was obtained with rates higher than 85 kg ai/ha. Sodium azide at 57 and 84 kg ai/ha controlled root diseases and weeds similarly to MB (Rodriguez-Kabana et al. 2004). In addition, sodium azide at 112 kg ai/ha combined with CP was equivalent to MB in weed control (Kabir et al. 2004).

The tarp applied immediately after application is important in fumigant efficiency. The combination of MS (468 L/ha) plus 1,3-D plus 17% CP (126 L/ha) provided good pest control and had high plant yield and vigor when covered with a polyethylene film immediately after treatment. The similar treatment not covered with polyethylene film but sealed with a mechanical soil cultipacker provided poor weed control (Csinos et al. 1997). MS plus CP without tarp provided grass control similar to MB, but it was reduced at five weeks after treatment (Unruh et al. 2002).

MB plus CP, MeI plus CP, Telone II (1,3-D 97.5%), Telone C-35 (1,3-D 63%) with high density polyethylene, and Telone C-35 with a virtually impermeable film were as effective as MB in reducing the viability of the seeds of field bindweed (*Convolvulus arvensis* L.), annual morningglory, johnsongrass (*Sorghum halepense* L.), and common purslane. However, none of the treatments reduced seed viability of little mallow. In addition, alternative treatment required similar amount of time to hand weed as MB treatment (Shrestha et al. 2004).

Application of emulsified formulations of 1,3-D, CP, and MS through drip irrigation system provided equal or better weed control than equivalent rates applied by shank injection (Fennimore et al. 2003). There was no nutsedge control where Telone C-35 was applied broadcast, but when applied in bed or broadcast followed by in bed application of CP, nutsedge control was comparable to MB (Gilreath et al. 2002).

Economic impact of MB phaseout was evaluated by other authors. Hueth et al. (2000), analyzed the economic aspect of MB replacement by MeI, a strong candidate from technical point of view. Sources of raw material, product cost, and supply-demand analysis is presented. Even though the economic aspect and the cost analysis play an important role in defining which product or production management will be adopted, this point goes beyond the scope of our work.

Even though there are numerous ways to control diseases and pests as mentioned previously, this research studied the potential of five soil fumigants: metham sodium, chloropicrin, 1,3-Dichloropropene, methyl iodide, dazomet and their combinations to replace MB in weed control and their influence in growth of six ornamental plants: *Euphorbia polychroma*, *Echinops bannaticus* 'Blue Globe', *Lavandula angustifolia* 'Hidcote Blue', *Hosta* 'Twilight PP14040', *Artemisia schmidtiana* 'Silver Mound', *Chrysanthemum x superbum* 'Snow Lady' and *Coreopsis verticillata* 'Moon Beam'

MATERIALS AND METHODS

The experiment was conducted in cooperation with an operational nursery, Hudsonville, Michigan. The soil in the site is a sandy loam soil with 81% sand, 8% silt and 11% clay. The soil pH was 6.2, phosphorus and magnesium concentrations in the soil

were the optimum and potassium was slightly below the optimum for ornamental crop production.

Fifteen treatments were applied on September 12, 2002 (Table 2). Each treatment was tarped immediately after application, except for one of the non-treated controls, one of the MS plots, and the dazomet plot, which remained uncovered. Weather conditions at application were: 24 C air temperature, soil moistures 0.1 to 0.2 (cm³/cm³), relative humidity 36%, soil temperature at 5 cm and 12 cm depth, 25.5 C and 22.2 C respectively, and wind speed was 8 km/h from the W. Plots were 1.22 m wide and 30.5 m long.

The fumigants were injected about 15 to 20 cm below the surface with a nitrogen pressurized fumigation rig at a pressure of 550 to 827 kPa (80-120 psi), mounted on a tractor with eleven chisels per bed spaced 30 cm apart. Dazomet is a granular fumigant which was applied evenly over the plot surface and incorporated immediately after application with a rototiller.

Seven ornamental species were planted mechanically in June 2003 (nine months after treatment): *Euphorbia polychroma*, *Echinops bannaticus* 'Blue Globe', *Lavandula angustifolia* 'Hidcote Blue', *Hosta* 'Twilight PP14040', *Artemisia schmidtiana* 'Silver Mound', *Chrysanthemum x superbum* 'Snow Lady' and *Coreopsis verticillata* 'Moon Beam'. The number of plants planted in each plot varied among species: 15 to 20 *Lavandula* plants, 6 to 8 plants of *Euphorbia polychrome*, *Echinops bannaticus*, and *Hosta*, and a complete row (25 to 30 plants) of *Chrysanthemum x superbum* and *Coreopsis verticillata*.

Plant injury was rated on July 23, 2003 and August 20, 2003. Rating was done visually in a range of 1 to 10, meaning 1 no injury and 10 dead plant. Weed evaluation

was done on April 24, July 9, 2003, and May 7, 2004. Plant size was measured on November 14, 2003 and May 19, 2004. Plant size index was determined by adding the highest point and the widest point of the plant and dividing by two (Briggs and Whitwell 2002).

Plant samples were taken from each plot and from each cultivar during September to October 2004. The number of plants per sample was between four and six depending on the number of plants present in the field. The plants were kept in a refrigeration room at 5 C until each plant was cut in the transition zone between roots and foliage. Foliage and roots from each plant were weighed fresh and after drying at 40 C for 7 to 10 days until a constant dry weight was achieved.

A randomized complete block design was used for weed control statistical analysis and split plot design was used for all measurements taken on the crop (injury, size index, fresh weight, and dry weight). A split plot design is justified by assigning fumigant treatments randomly to the main plots as a first step and cultivars (subplot) were allocated within each treatment as a second step. The site had six replications. Replications 1, 3, and 5 contained 15 treatments; and replications 2, 4, and 6 contained 14 treatments; the difference is because dazomet treatment was applied only in the odd numbered replications.

RESULTS AND DISCUSSION

All treatments controlled 80% to 100% of annual weeds, except MeI 50% plus CP 50% (224 kg/ha, tarped) and MS (1:4 water, 701 L/ha, not tarped), which resulted in lower control of common chickweed, mouseear cress (*Arabidopsis thaliana* (L.) Heynh.)

on April 2003 and May 2004 (Table 3 and 5), and common lambsquarters and common purslane on July 2004 (Table 4). However, MeI 50% plus CP 50% at higher rate (336 kg/ha, tarped) had good control of these weeds, suggesting that the rate of 224 kg/ha was below the threshold for weed control and the most efficient rate should be between 224 and 336 kg/ha. MS (1:4 water, 701 L/ha, not tarped) did not control weeds well as in the same treatment tarped, indicating that tarping the plot after fumigation was an important factor in controlling weeds. This result agrees with Csinos et al, 1997, who found that pest control, yield and plant vigor were greater in MS (468 L/ha) plus 1,3-D plus 17% CP (126 L ha⁻¹) covered with polyethylene; and Unruh et al, 2002 who found that MS plus CP without tarp provided good weed control but for a short period (5 weeks).

Crop injury was not noticeable in any of the treatments on July 23, 2003 (data not shown). However on August 20, 2003 a slight injury (1.7 from 10) was observed in *Euphorbia* with Telone C-35 (1,3-D, 65%) 327 L/ha tarped, MeBr (98%) plus 2% CP 392 kg/ha tarped, MeI (98%) plus 2% CP 168 kg/ha tarped, and MeBr (67%) plus 33% CP 392 kg/ha tarped when compared with the control (Table 6). Fumigant modes of action are not well known, so specific or particular fumigant lesions can not be expected, which makes it difficult to separate fumigant injury from other causes like diseases that could affect plants in the same manner.

There were no differences in plant size between treatments on November 2003 (data not shown) and on May 2004 (Table 7), except for *Euphorbia* in 2004, in which plants were smaller in the same treatments where injury was observed.

Considering fresh weight, treatments Telone C-35 (1,3-D, 65%) 327 L/ha tarped and MeI (98%) plus 2% CP 168 kg/ha tarped reduced *Euphorbia* weight. All treatments,

except MS 701 L/ha (1:4 water, not tarped), reduced *Lavandula* weight, compared to the control. The other species had either no difference in weight or treatments resulted in heavier plants compared to the control. However, considering total dry weight analysis there were no significant differences between treatments except for *Euphorbia* and *Artemisia* (Table 8). Telone C-35 (1,3-D 65% plus CP 35%) 327 L/ha tarped reduced ($P<0.05$) total plant weight in *Euphorbia* compared to the control. Furthermore, this reduction in weight was caused by a reduction in root and foliage biomass (Table 9). MeI plus CP (50:50) 336 kg/ha tarped caused the lowest plant weight in *Artemisia*, but was not significantly different from the control. In addition root and foliage biomass were not different from the control.

Dazomet was not included for the statistical analysis because it was not applied in all blocks and results obtained from this application would greatly influence the overall results. As a general comment, dazomet gave good weed control in the three evaluation dates except for prickly lettuce (*Lactuca serriola* L.) in May 2004. This fumigant injured slightly *Euphorbia* (2.6 out of 10) and produced the smallest plants in this species. Dazomet treatment provided the lowest fresh weight in all species except for *Hosta*, which was not significantly different, and for *Artemisia*, which resulted in heavier plants compared to the control. Considering dry weight, dazomet treatment resulted in the lowest biomass in *Euphorbia*, *Lavandula* and *Coreopsis* (Table 10). However, the reduced number of replications may not allow us to compare these results directly with other treatments.

CONCLUSIONS

Most fumigants tested had good weed control up to 20 months after application. MeI 50% plus 50% CP (tarped, 224 kg/ha) and MS not tarped (701 L/ha, 1:4 water) had the poorest control of most summer annual weeds. In the first case, lower rate and in the second case, tarp could be the factors that contributed to the poor weed control.

In general, most fumigants did not injure the ornamental crops evaluated in this experiment. Minor injury to *Euphorbia* caused by some treatments was reflected in the size when measured in November 2003 and May 2004 and in plant biomass weight at end of experiment. However, as mentioned previously, fumigants mode of action is not known in detail and plant response to them could be variable, thus, making it difficult to separate fumigant injuries from other causes. In addition, further investigation needs to be done to determine if any other variable could have been the cause of this injury and smaller *Euphorbia* plants.

All of the fumigants tested have a potential to replace MB. They had good weed control and did not interfere with crop development and yield. Further studies in fumigant decomposition, interaction with the environment, effects in other ornamentals and human effects are required in order to use them safely. Furthermore, fumigants combined with herbicides are promising options for weed control in the ornamental industry, thus further research in this area is needed in order to evaluate the real potential.

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Table 1. Properties of the soil fumigants.

Comon name	Trade name	Formulation	Status	Pest control activity
Methyl Bromide	Brom-o-Gas	MB 98% + CP 2%	Registered	Nematodes, weeds, fungi, insects
Methyl Bromide	Terro-gas-67	MB 67% + CP 33%	Registered	Nematodes, weeds, fungi, insects
Metham sodium	Vapam	Sodium methylthiocarbamate 42% + 58% inerts	Registered	Nematodes, weeds, fungi, insects
Chloropicrin	Chloropicrin	Chloropicrin 99.5%	Registered	Nematodes, fungi, insects
1,3-D	Telone II	1,3-Dichloropropene 97.5%	Registered	Nematodes, fungi, insects
1,3-D	Telone C-35	1,3-Dichloropropene 65% + 35% CP	Registered	Nematodes, fungi, insects
1,3-D	Telone C-17	1,3-Dichloropropene 83% + 17% CP	Registered	Nematodes, fungi, insects
1,3-D	Telone EC	1,3-Dichloropropene 93.6 %	Registered	Nematodes, fungi, insects
Dazomet	Basamid	Dazomet granular 99%	Registered	Nematodes, weeds, fungi, insects
Methyl iodide	Methyl iodide	MeI 98% + CP 2%	Not registered	Nematodes, weeds, fungi
Methyl iodide	Methyl iodide	MeI 50% + CP 50%	Not registered	Nematodes, weeds, fungi
Propylene oxide	Propozone	Propylene oxide 100%	Not registered	Nematodes, fungi
Propargyl bromide	INA	INA	Not registered	INA
Sodium azide	Sep-100	INA	Not registered	Nematodes, weeds, fungi

INA: information not available

Table 2. Fifteen pesticide treatments evaluated at Sawyers Nursery (Hudsonville, MI) for management of weeds and nematodes in *Euphorbia polychroma*, *Echinops bannaticus*, *Lavandula angustifolia*, *Hosta*, *Artemisia schmidtiana*, *Chrysanthemum x superbum* and *Coreopsis verticillata*.

N°	Treatment	Tarp	Rate
1	Non-treated	No	---
2	Non-treated (tarped)	Yes	---
3	Methyl iodide (50%) + 50% chloropicrin	Yes	336 kg/ha
4	Methyl iodide (50%) + 50% chloropicrin	Yes	224 kg/ha
5	Telone C-35 *	Yes	327 L/ha
6	Methyl Bromide (98%) + 2% chloropicrin	Yes	392 kg/ha
7	Methyl iodide (98%) + 2% chloropicrin	Yes	168 kg/ha
8	Metham sodium	No	701 L/ha (1:4 water)
9	Metham sodium	Yes	701 L/ha (1:2 water)
10	Metham sodium	Yes	701 L/ha (1:4 water)
11	Telone II **	Yes	327 L/ha
12	Telone II **and Metham	Yes	327 L/ha + 701 L/ha (1:4 water)
13	Methyl Bromide (67%)+ 33% chloropicrin	Yes	392 kg/ha
14	Telone C-35 *and Metham	Yes	327 L/ha + 701 Lt/ha (1:4 water)
15	Dazomet	No	393 kg/ha

* Telone C-35: 1,3 dichloropropene 63.4%, chloropicrin 34.7%

** Telone II: 1,3 dichloropropene 97.5%.

Table 3. Weed evaluation at seven months after soil fumigants application.¹

Treatment	Tarp	Rate	24-Apr-03		
			STEME ³	SENVU	ARBTH
			-----Control rating ² -----		
Non-treated	No	---	1.0 e	1.0 b	1.0 c
Non-treated (tarpd)	Yes	---	6.3 b	8.1 a	7.0 b
MeI (50%) + 50% CP	Yes	336 kg/ha	9.8 a	10 a	9.8 a
MeI (50%) + 50% CP	Yes	224 kg/ha	2.1 d	6.0 b	1.8 c
1,3-D (65%)	Yes	327 L/ha	9.8 a	10 a	9.3 a
MB (98%) + 2% CP	Yes	392 kg/ha	9.8 a	10 a	10 a
MeI (98%) + 2% CP	Yes	168 kg/ha	9.8 a	10 a	9.5 a
MS	No	701 L/ha (1:4 water)	5.0 c	9.7 a	3.0 c
MS	Yes	701 L/ha (1:2 water)	9.3 a	10 a	9.0 a
MS	Yes	701 L/ha (1:4 water)	9.7 a	10 a	9.5 a
1,3-D (97.5%)	Yes	327 L/ha	10 a	10 a	10 a
1,3-D (97.5%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	10 a	10 a	10 a
MB (67%)+ 33% CP	Yes	392 kg/ha	10 a	10 a	10 a
1,3-D (65%) + MS	Yes	327 L/ha + 701 Lt/ha (1:4 water)	9.7 a	10 a	9.8 a

¹ Means within a column with the same letter are not significantly different at P=0.05.

² Control was evaluated on a scale 1 to 10. Meaning 1=no control and 10 =total control.

³ List of weeds: STEME: *Stellaria media*(L.) Vill., SENVU: *Senecio vulgaris* L., ARBTH: *Arabidopsis Thaliana* L.

Table 4. Weed evaluation at 10 months after soil fumigants application.¹

Treatment	Tarp	Rate	9-Jul-03				
			CHEAL ³	POROL	AMARE	SETLU	SENVU
			----- Control rating ² -----				
Non-treated	No	---	1.0 d	1.0 c	1.0 c	1.0 c	1.0 b
Non-treated (tarped)	Yes	---	1.0 d	1.0 c	1.0 c	1.0 c	1.0 b
MeI (50%) + 50% CP	Yes	336 kg/ha	10 a	9.2 a	10 a	10 a	9.8 a
MeI (50%) + 50% CP	Yes	224 kg/ha	8.3 bc	5.7 b	8.8 a	9.5 a	8.3 a
1,3-D (65%)	Yes	327 L/ha	9.7 ab	8.7 a	9.8 a	10 a	10 a
MB (98%) + 2% CP	Yes	392 kg/ha	10 a	9.2 a	10 a	10 a	9.7 a
MeI (98%) + 2% CP	Yes	168 kg/ha	10 a	9.3 a	10 a	10 a	9.8 a
MS	No	701 L/ha (1:4 water)	7.5 c	5.0 b	9.5 a	8.5 a	9.5 a
MS	Yes	701 L/ha (1:2 water)	10 a	9.0 a	9.7 a	10 a	9.7 a
MS	Yes	701 L/ha (1:4 water)	10 a	9.2 a	10 a	10 a	10 a
1,3-D (97.5%)	Yes	327 L/ha	10 a	9.3 a	10 a	10 a	9.7 a
1,3-D (97.5%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	10 a	9.5 a	10 a	10 a	9.8 a
MB (67%)+ 33% CP	Yes	392 kg/ha	10 a	9.7 a	10 a	10 a	9.8 a
1,3-D (65%) + MS	Yes	327 L/ha + 701 Lt/ha (1:4 water)	10 a	9.5 a	10 a	10 a	10 a

¹ Means within a column with the same letter are not significantly different at P=0.05.

² Control was evaluated on a scale 1 to 10. Meaning 1=no control and 10 =total control.

³ List of weeds: CHEAL: *Chenopodium album* L, POROL: *Portulaca oleracea* L., AMARE: *Amarantus retroflexus* L., SETLU: *Setaria glauca* (L.) Beauv., SENVU: *Senecio vulgaris* L.

Table 5. Weed evaluation at 20 months after soil fumigants application.¹

7-May-04							
Treatment	Tarp	Rate	ARBTH ³	STEME	TRFPR	LACSE	MALNE
-----Control rating ² -----							
Non-treated	No	---	1.0 e	1.0 c	1.0 c	1.0 c	1.0 c
Non-treated (tarped)	Yes	---	1.0 e	1.0 c	1.0 c	1.0 c	1.0 c
MeI (50%) + 50% CP	Yes	336 kg/ha	7.5 ab	8.5 a	9.5 ab	6.8 abc	10 a
MeI (50%) + 50% CP	Yes	224 kg/ha	4.0 cd	2.6 c	10 a	8.3 ab	9.0 a
1,3-D (65%)	Yes	327 L/ha	8.7 a	8.5 a	8.3 ab	6.7 abc	9.2 a
MB (98%) + 2% CP	Yes	392 kg/ha	8.3 a	8.2 a	7.0 b	6.0 bc	9.5 a
MeI (98%) + 2% CP	Yes	168 kg/ha	8.0 a	8.5 a	8.7 ab	6.7 abc	10 a
MS	No	701 L/ha (1:4 water)	5.8 bc	4.5 b	9.7 a	7.0 ab	9.8 a
MS	Yes	701 L/ha (1:2 water)	8.3 a	8.3 a	9.5 ab	7.3 ab	9.2 a
MS	Yes	701 L/ha (1:4 water)	8.8 a	8.5 a	9.0 ab	7.3 ab	10 a
1,3-D (97.5%)	Yes	327 L/ha	7.6 ab	7.8 a	9.8 a	9.0 a	8.6 a
1,3-D (97.5%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	8.7 a	9.0 a	8.7 ab	5.8 bc	8.0 a
MB (67%)+ 33% CP	Yes	392 kg/ha	7.2 ab	7.8 a	8.8 ab	7.2 ab	9.2 a
1,3-D (65%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	7.8 a	8.0 a	8.2 ab	6.2 abc	8.4 a

¹ Means within a column with the same letter are not significantly different at P=0.05.

² Control was evaluated on a scale 1 to 10. Meaning 1=no control and 10 =total control.

³ Weed listed: ARBTH: *Arabidopsis Thaliana* (L.) Heynh, STEME: *Stellaria media*(L.) Vill., TRFPR: *Trifolium pratense* L., LACSE: *Lactuca serriola* L., MALNE: *Malva neglecta* Wallr.

Table 6. Ornamental species injury rates at eleven months after soil fumigants application.¹

Treatment	Tarp	Rate	20-Aug-03					
			Euphorbia ³	Echinops	Lavandula	Hosta	Artemisia	Chrysanth.
			Injury ²					
Non-treated	No	---	1.0 c	1.0 a	1.0 a	1.0 a	1.0 a	1.0 a
Non-treated (tarped)	Yes	---	1.2 bc	1.0 a	1.0 a	1.0 a	1.0 a	1.0 a
MeI (50%) + 50% CP	Yes	336 kg/ha	1.2 bc	1.2 a	1.0 a	1.0 a	1.0 a	1.2 a
MeI (50%) + 50% CP	Yes	224 kg/ha	1 c	1.0 a	1.0 a	1.0 a	1.0 a	1.2 a
1,3-D (65%)	Yes	327 L/ha	1.7 a	1.3 a	1.0 a	1.0 a	1.0 a	1.0 a
MB (98%) + 2% CP	Yes	392 kg/ha	1.5 ab	1.0 a	1.0 a	1.0 a	1.0 a	1.0 a
MeI (98%) + 2% CP	Yes	168 kg/ha	1.5 ab	1.2 a	1.0 a	1.0 a	1.0 a	1.0 a
MS	No	701 L/ha (1:4 water)	1.3 abc	1.0 a	1.0 a	1.0 a	1.0 a	1.2 a
MS	Yes	701 L/ha (1:2 water)	1.2 bc	1.0 a	1.2 a	1.0 a	1.0 a	1.0 a
MS	Yes	701 L/ha (1:4 water)	1.3 abc	1.0 a	1.0 a	1.0 a	1.0 a	1.0 a
1,3-D (97.5%)	Yes	327 L/ha	1.3 abc	1.3 a	1.0 a	1.0 a	1.0 a	1.3 a
1,3-D (97.5%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	1.0 c	1.3 a	1.0 a	1.0 a	1.0 a	1.2 a
MB (67%)+ 33% CP	Yes	392 kg/ha	1.7 a	1.2 a	1.0 a	1.2 a	1.0 a	1.0 a
1,3-D (65%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	1.0 c	1.0 a	1.2 a	1.0 a	1.0 a	1.2 a

¹ Means within a column with the same letter are not significantly different at P=0.05

² Injury was rated visually on a 1 to 10 scale, meaning 1 = no injury and 10 = dead plant

³ Significant differences were observed only in Euphorbia

Table 7. Plant size index¹ of 7 perennials growing in plots treated with different fumigant combinations.²

Treatment	Tarp	Rate	19-May-04						
			Euphorbia ³	Hosta	Echinops	Lavandula	Artemisia	Chrysanth.	Coreopsis
			----- cm -----						
Non-treated	No	---	47.0 ab	13.5 a	38.1 a	32.5 a	16.6 a	23.3 a	35.0 a
Non-treated (tarped)	Yes	---	46.7 ab	13.9 a	39.2 a	31.3 a	16.7 a	23.5 a	34.8 a
MeI (50%) + 50% CP	Yes	336 kg/ha	43.6 ab	15.2 a	39.5 a	33.4 a	17.0 a	22.4 a	36.4 a
MeI (50%) + 50% CP	Yes	224 kg/ha	48.0 a	13.5 a	41.9 a	30.7 a	18.9 a	23.2 a	35.2 a
1,3-D (65%)	Yes	327 L/ha	38.2 c	15.8 a	41.0 a	33.2 a	21.4 a	23.5 a	38.0 a
MB (98%) + 2% CP	Yes	392 kg/ha	40.8 c	14.5 a	43.6 a	34.2 a	20.2 a	21.1 a	36.2 a
MeI (98%) + 2% CP	Yes	168 kg/ha	39.9 c	16.0 a	36.2 a	34.0 a	22.3 a	23.3 a	38.6 a
MS	No	701 L/ha (1:4 water)	43.8 ab	15.0 a	42.1 a	33.4 a	17.9 a	22.8 a	35.9 a
MS	Yes	701 L/ha (1:2 water)	45.9 ab	14.5 a	42.0 a	30.9 a	17.4 a	21.3 a	37.5 a
MS	Yes	701 L/ha (1:4 water)	46.2 ab	14.9 a	43.3 a	31.2 a	20.0 a	22.9 a	38.8 a
1,3-D (97.5%)	Yes	327 L/ha	42.3 bc	14.8 a	39.1 a	33.0 a	20.3 a	22.5 a	37.5 a
1,3-D (97.5%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	45.2 ab	13.5 a	40.9 a	31.4 a	20.6 a	23.3 a	38.1 a
MB (67%)+ 33% CP	Yes	392 kg/ha	40.5 c	14.3 a	38.5 a	31.5 a	21.1 a	23.0 a	38.1 a
1,3-D (65%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	45.5 ab	14.9 a	41.3 a	31.9 a	22.1 a	22.8 a	37.0 a

¹ Size index= (height + width)/2

² Means within a column with the same letter are not significantly different at P=0.05

³ Euphorbia showed significant differences.

Table 8. Total plant dry matter of the seven ornamental species evaluated.¹

Treatment	Tarp	Rate	Euphorbia	Hosta	Echinops	Lavandula	Artemisia	Chrysanth.	Coreopsis
----- kg / plot sample -----									
Non-treated	No	---	1.77 ab	0.14 a	1.11 a	2.21 a	1.95 d	1.06 a	2.45 abc
Non-treated (tarped)	Yes	---	1.87 ab	0.13 a	1.15 a	2.05 a	2.19 bcd	1.07 a	2.14 c
MeI (50%) + 50% CP	Yes	336 kg/ha	1.48 ab	0.20 a	1.01 a	1.70 a	1.97 cd	1.11 a	2.17 c
MeI (50%) + 50% CP	Yes	224 kg/ha	1.74 ab	0.15 a	1.33 a	1.96 a	2.26 bcd	0.96 a	2.5 abc
1,3-D (65%)	Yes	327 L/ha	0.82 c	0.19 a	1.19 a	2.15 a	2.57 ab	1.06 a	2.40 abc
MB (98%) + 2% CP	Yes	392 kg/ha	1.34 bc	0.15 a	1.03 a	1.85 a	2.65 a	1.11 a	2.40 abc
MeI (98%) + 2% CP	Yes	168 kg/ha	1.34 bc	0.18 a	0.90 a	1.92 a	2.47 abcd	1.20 a	2.43 abc
MS	No	701 L/ha (1:4 water)	1.50 ab	0.17 a	1.25 a	2.23 a	2.27 bcd	1.10 a	2.50 abc
MS	Yes	701 L/ha (1:2 water)	1.94 a	0.17 a	1.31 a	1.94 a	2.35 abcd	1.10 a	2.76 a
MS	Yes	701 L/ha (1:4 water)	1.84 ab	0.18 a	1.14 a	1.78 a	2.59 ab	0.96 a	2.6 ab
1,3-D (97.5%)	Yes	327 L/ha	1.37 bc	0.16 a	1.11 a	2.08 a	2.51 ab	1.14 a	2.23 bc
1,3-D (97.5%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	1.77 ab	0.14 a	1.08 a	1.79 a	2.17 bcd	1.05 a	2.53 ab
MB (67%)+ 33% CP	Yes	392 kg/ha	1.37 bc	0.14 a	1.04 a	1.90 a	2.11 bcd	1.23 a	2.40 abc
1,3-D (65%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	1.37 bc	0.19 a	1.15 a	1.79 a	2.35 abcd	1.12 a	2.36 abc

¹ Means within a column with the same letter are not significantly different at P=0.05

Table 9. Roots, foliage, and total plant dry weight of *Euphorbia* and *Artemisia*.¹

Treatment	Tarp	Rate	Euphorbia			Artemisia		
			Total weight	Foliage	Root	Total weight	Foliage	Root
			----- kg / plot sample-----			----- kg / plot sample -----		
Non-treated	No	---	1.772 ab	0.873 a	0.899 a	1.889 d	1.203 c	0.686 b
Non-treated (tarped)	Yes	---	1.872 ab	0.925 a	0.947 a	2.073 bcd	1.288 bc	0.785 ab
MeI (50%) + 50% CP	Yes	336 kg/ha	1.477 ab	0.693 ab	0.784 a	1.940 cd	1.272 bc	0.668 b
MeI (50%) + 50% CP	Yes	224 kg/ha	1.744 ab	0.828 a	0.920 a	2.150 bcd	1.461 bc	0.690 b
1,3-D (65%)	Yes	327 L/ha	0.820 c	0.363 b	0.473 b	2.623 ab	1.615 ab	1.008 a
MB (98%) + 2% CP	Yes	392 kg/ha	1.341 bc	0.606 ab	0.734 ab	2.725 a	1.738 a	0.987 a
MeI (98%) + 2% CP	Yes	168 kg/ha	1.341 bc	0.585 ab	0.756 ab	2.438 abcd	1.567 bc	0.872 ab
MS	No	701 L/ha (1:4 water)	1.501 ab	0.742 a	0.759 ab	2.159 bcd	1.376 bc	0.784 ab
MS	Yes	701 L/ha (1:2 water)	1.942 a	0.951 a	0.991 a	2.415 abcd	1.502 bc	0.913 ab
MS	Yes	701 L/ha (1:4 water)	1.839 ab	0.955 a	0.884 a	2.583 ab	1.586 ab	0.997 a
1,3-D (97.5%)	Yes	327 L/ha	1.372 bc	0.647 ab	0.725 ab	2.620 ab	1.654 a	0.967 a
1,3-D (97.5%) + MS	Yes	327 L/ha + 701 L/ha (1:4 water)	1.770 ab	0.860 a	0.910 a	2.141 bcd	1.237 c	0.905 ab
MB (67%)+ 33% CP	Yes	392 kg/ha	1.372 bc	0.690 ab	0.682 b	2.214 bcd	1.463 bc	0.751 ab
1,3-D (65%) + MS	Yes	327 L/ha + 701 Lt/ha (1:4 water)	1.370 bc	0.671 ab	0.699 b	2.363 abcd	1.460 bc	0.903 ab

¹ Means within a column with the same letter are not significantly different at P=0.05

Table 10. Effect of Dazomet on ornamental plant visual rating, size, and dry weight.¹

	Euphorbia	Echinops	Lavandula	Hosta	Artemisia	Chrysanthemum	Coreopsis
	Injury rating-----						
Untreated	1.0 a	1.0 a	1.0 a	1.0 a	1.0 a	1.0 a	1.0 a
Dazomet	2.6 b	1.7 a	1.6 a	1.0 a	1.0 a	1.0 a	1.3 a
	----- Size (height+width/2) (cm)-----						
Untreated	46.1 a	43.4 a	32.9 a	14.6 a	21.0 a	25.0 a	37.9 a
Dazomet	23.5 b	38.8 a	26.7 a	14.6 a	21.4 a	24.4 a	35.8 a
	----- Fresh weight (kg/plant) ² -----						
Untreated	0.92 a	0.50 a	1.07 a	0.07 a	0.80 a	0.72 a	0.94 a
Dazomet	0.32 b	0.26 b	0.43 b	0.06 a	1.07 b	0.55 b	0.77 b
	----- Dry weight (kg/plot) ³ -----						
Untreated	1.29 a	1.19 a	2.25 a	0.11 a	2.27 a	1.02 a	2.56 a
Dazomet	0.53 b	0.73 a	1.28 b	0.14 a	2.30 a	0.91 a	2.03 b

¹ Means within a column with the same letter are not significantly different at P=0.05

² Fresh weight means considers the average weight per plant.

³ Dry weight mean of all plants in the plot.

**CHAPTER IV: RESPONSE OF TEN ORNAMENTAL SPECIES TO HERBICIDE
TREATMENTS**

INTRODUCTION

Nursery and greenhouse production of ornamental plants represents the sixth largest agricultural commodity group in the United States. This is the fastest growing segment of the U.S. agriculture; between 1991 and 1998 sales of ornamentals increased 30%. Growth in ornamental sales is caused by the strong U.S. economy with the expansion in housing and increase of ornamental plant consumption (Knox et al. 2003).

Ornamental and floriculture nurseries in California, Florida, Michigan, Oregon, Pennsylvania, and Texas used 335 pesticide active ingredients and a total of 2.2 million kg of chemicals in 2003; herbicides accounted for 20% (446,000 kg) of the total amount used. Among herbicides, glyphosate is the most popular, being used in 26% of the operations, followed by oxyfluorfen with 8%, and oryzalin with 6% of the operations (Anonymous 2004).

Economic losses of nurseries due to weed infestations have been estimated to be about \$7,000 per acre. Nurseries may spend \$500 to \$4000 per acre of containers for manual removal of weeds (Mathers and Case 2003). However, hand-weeding sometimes is necessary regardless of preventative measures utilized for weed control (Knox et al. 2003). Cultivation may damage herbaceous perennial species because storage organs (bulbs, rhizomes, roots) are located just below the soil surface. Herbicides usually reduce weed control costs; however, little information about tolerance of herbaceous perennials to herbicides is available and very few herbicides are labeled for use on ornamentals (Calkins et al. 1996).

Methyl bromide (MB) fumigation has been used widely to control soil borne diseases and nematodes, and a wide spectrum of weeds. However, due to the Montreal

Protocol decision to phase out MB because of its harmful effect on the ozone layer, it may not be available to growers after 2005. As a consequence, herbicides will become more important in weed control programs for ornamentals.

A number of herbicides are registered for some ornamental crops. Terbacil belongs to the uracil chemical family. This herbicide inhibits photosynthesis by binding to the Q_b -binding niche on the D1 protein of the photosynthesis II complex. Terbacil controls many annual broadleaf and grass weeds, including common chickweed (*Stellaria media* (L.) Vill.), henbit (*Lamium amplexicaule* L.), common lambsquarters (*Chenopodium album* L.), prickly lettuce (*Lactuca serriola* L.), crabgrass (*Digitaria* spp.), downy brome (*Bromus tectorum* L.), foxtail (*Setaria* spp.), ryegrass (*Lolium* spp.), and barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.), with partial control of nutsedge (*Cyperus* spp.). Its half life is four months (Vencill 2002).

Imazapic, imazaquin, and halosulfuron are herbicides that inhibit acetolactate synthase (ALS), a key enzyme in the biosynthesis of the branched-chain amino acids isoleucine, leucine, and valine. Imazapic and imazaquin belong to the imidazolinone chemical family while halosulfuron belongs to the sulfonyleurea chemical group. Their main symptoms are growth inhibition, chlorosis, and necrosis. Halosulfuron applied pre emergence does not inhibit seed germination, but as soon they emerge symptoms are observed. In addition halosulfuron persistence varies with the soil type from 7 to 34 days (Vencill 2002).

Halosulfuron applied foliarly at 0.009 and 0.018 kg/ha provided 87 to 91% purple nutsedge control and 79 to 84% yellow nutsedge control. Regrowth measurements taken 5 WAT showed 88 to 90% reduction in purple nutsedge resprouting and 75 to 83%

reduction in yellow nutsedge resprouting (Hurt and Vencill 1994a). Halosulfuron applied with 0.25 and 0.5% (v/v) adjuvants such as X-77, Scoil, Sun-It II, Agridex, and Action "99", injured Japanese holly, forsythia, green liriopse, and weigela but not 'Blue Girl' holly (*Ilex x meserveae* S.Y. Hu 'Blue girl') (McDaniel et al. 1999). Azalea, redbud, photinia, green liriopse, white petunias, red petunias, lavender petunias, celosia, vinca, African marigold, bronze-leaved begonias, and purple salvia tolerated 0.009 and 0.018 kg/ha of halosulfuron (Hurt and Vencill 1994a). In addition *Ilex x meserveae* S.Y. Hu 'China girl' showed no visual injury or growth reduction from applications of halosulfuron at 0.017, 0.035, 0.070 kg ai/ha, imazaquin at 0.035, 0.070, 0.14 kg ai/ha or isoxaben at 0.56, 1.12, 2.24 kg ai/ha (Altland et al. 2000).

Imazaquin provided excellent control of large crabgrass (*Digitaria sanguinalis* (L.) Scop.), redroot pigweed, Pennsylvania bittercress (*Cardamine pennsylvanica* Muhl. ex. Willd.), common chickweed, yellow woodsorrel (*Oxalis stricta* L.), and creeping woodsorrel (*Oxalis corniculata* L.) at 0.56 kg ai/ha for 14 weeks, but was phytotoxic to vegetative azaleas (Moore et al. 1989). Imazaquin was one of the most effective PRE treatments for reducing yellow nutsedge shoot weight. Furthermore, imazaquin applied POST reduced yellow nutsedge shoot weight by 72 to 87% at 2 WAT, comparable to chlorimuron, pyridate, bentazon, and glyphosate (Derr and Wilcut 1993). Hurt et al. (1994a) obtained 70 to 77% yellow nutsedge control and 56 to 59% purple nutsedge control with imazaquin applied at 0.430 kg/ha and 0.560 kg/ha, respectively.

Foliar applications of imazapic at 0.07 g/ha controlled 95% of purple nutsedge and 61% of yellow nutsedge; however Azalea 'Macrantha Orange' was not tolerant to any of the imidazolinone herbicides tested. Green liriopse was tolerant of all herbicide

treatments 4 WAT (Hurt and Vencill 1994b). The application method of imazapic can injure the following crop. Imazapic was more injurious to cotton when applied preplant incorporated to the preceding peanut crop, compared with postemergence application. Imazapic applied preplant incorporated at 0.07 and 0.14 kg/ha visibly injured cotton 19 to 58%. The same rate applied postemergence caused minor injury to cotton but did not affect yield (York et al. 2000).

The incorporation of adjuvants in the tank mix can affect the herbicide efficacy. The benefit of adjuvants appears greater for imazethapyr than imazapic. No advantage in purple nutsedge control was observed when adjuvants were added to imazapic (Grichar and Sestak 2000).

Imazaquin visibly injured barberry (10 to 18%), liriope (0 to 21%), daylily (0 to 25%), compacta “holly” (0 to 8%), azalea (35 to 39%), photinia (0 to 19%), and did not injure Burford holly and juniper. Imazaquin at 0.25 and 0.5 kg/ha reduced growth of azalea, liriope and daylily (Derr and Wilcut 1993).

Visual ratings may not detect injury from imidazolinone herbicides to certain nursery species. Although no observable injury was evident 5 WAT, imazethapyr reduced juniper size indices. There are different responses between woody nursery crops and herbaceous species; the woody nursery crops outgrew the visible damage from chlorimuron observed 5 WAT as no reduction in size was noted 10 WAT. However, growth of the herbaceous species liriope and daylily was reduced by this herbicide, indicating that chlorimuron has a greater potential for use in woody species (Derr and Wilcut 1993).

Flumioxazin belongs to the N-phenyphthalimide chemical family. It gives good preemergence control of many broadleaf weeds, including common ragweed, common lambsquarters, velvetleaf, pigweed, and black nightshade (*Solanum nigrum* L.). The mode of action is believed to be inhibition of protoporphyrinogen oxidase, an enzyme important in the synthesis of chlorophyll; after absorption, porphyrins accumulate in susceptible plants causing photosensibilization, which leads to membrane peroxidation. Plants emerging from treated soil become necrotic and die shortly after sunlight exposure (Vencill 2002). Flumioxazin affects photosynthesis by reducing foliar chlorophyll and carotenoid contents, gas exchanges and alteration in plastid structure. As a result, plantlet growth was greatly inhibited (Saladin et al. 2003). Hydrolysis and photolytic degradation rate increased with the pH increase, and the degradation products formed by photolysis were the same as those formed by hydrolysis (Kwon et al. 2004).

Flumioxazin alone controlled giant foxtail (*Setaria faberi* Herrm.) 18-81%, velvetleaf 83-88%, common ragweed 79-83%, ivyleaf morningglory (*Ipomoea hederacea* (L.)) 92-93%, and common waterhemp (*Amaranthus rudis* Sauer) 48-100%. Velvetleaf and ivyleaf morningglory control with flumioxazin was improved with the addition of clomazone plus chlorimuron or pendimethalin plus chlorimuron (Niekamp and Johnson 2001). The water dispersible granular formulation of flumioxazin at 0.19 kg ai/ha was the only treatment that caused injury on *Spirea bumalda*. The injury declined 4 weeks after application. In addition, this treatment resulted in the best large crabgrass and tall morningglory control. On the other hand, the poorest weed control was observed with the lowest rate (0.19 kg ai/ha) of the granular flumioxazin. Combinations with other herbicides such as isoxaben, dithiopyr, or dinitroaniline herbicide may increase and

broaden the weed control spectrum (Czarnota et al. 2001). Flumioxazin at 0.28, 0.42, and 0.56 kg ai/ha was safe on 'Nellie R. Stevens' holly (*Ilex* x 'Nellie R. Stevens'), arbutus (*Thuja occidentalis* 'Emerald'), and 'Green Luster' holly (*Ilex crenata* 'Green Luster'), but injured 'Goldmound' spirea (*Spirea* x 'Goldmound') and daylily (*Hemerocallis* x 'Stella de oro') (Wooten and Neal 2001).

Isoxaben belongs to the benzamide chemical family. Isoxaben can be applied in established turf, ornamentals, nursery stock, non-bearing fruit trees, and Christmas tree plantations. Isoxaben controls common chickweed, clover spp., dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), henbit, prostrate knotweed (*Polygonum aviculare* L.), plantain spp (*Plantago* spp), and many other annual broadleaf weeds. If applied pre-emergent, susceptible weeds fail to emerge. Isoxaben inhibits cell wall biosynthesis and broadleaf weeds show stunting, reduced root growth, root hair distortion, and root clubbing (swelling of meristematic and elongation zones) symptoms, similar to those caused by dinitroaniline herbicides. Isoxaben persistence in soil is moderate to long, with a half life of 50 to 120 days in field conditions; weed control extends to 6 months (Vencill 2002).

Isoxaben at 0.84 and 1.1 kg ai/ha did not provide acceptable control of large crabgrass, but prostrate spurge (*Euphorbia humistrata* Engelm. Ex Gray) was controlled 62 and 80%, respectively (Skroch et al. 1994). When the active ingredients isoxaben and oryzalin were applied in combination, weed control was better than that provided by either compound alone. Isoxaben plus oryzalin at 4.48 kg ai/ha and a tank mix of isoxaben (1.12 kg ai/ha) plus oryzalin (3.36 kg ai/ha) provided the best weed control, reducing the weed numbers by 93 to 99% respectively compared to control (Calkins et al.

1996). Isoxaben applied to dwarf burning bush (*Euonymus alatus* (Thunb) Sieb.

‘Compacta’) foliage caused 20 to 30% injury, but only slight reductions in root and shoot weight were observed. On the other hand, isoxaben at 0.84 and 1.69 kg/ha did not reduce shoot and root weight in wintercreeper (*Euonymus fortunei* (Turcz.) Hand. Mazz.

‘Colorata’ (Salihu et al. 1999).

Trifluralin belongs to the dinitroaniline chemical family. It is labeled for more than 80 crops. It is used on nursery stock, ornamental shrubs, groundcovers and established flowers. Trifluralin controls annual grasses and some small-seeded broadleaf weeds. This herbicide binds to tubulin, the major microtubule protein, resulting in absence of the spindle apparatus, thus preventing alignment and separation of chromosomes. Susceptible weeds fail to emerge, due to inhibition of coleoptile growth or hypocotyls unhooking. Roots appear stubby with thickened tips. The average life time in soil is 45 days for most soils, but depends on the temperature. Residues can persist to the following year with the possibility of crop injury (Vencill 2002).

Granular Rout (Oxyfluorfen 2% plus oryzalin 1%, 3.36 kg ai/ha), Snapshot TG (trifluralin 2% plus isoxaben 0.5%, 4.2 kg ai/ha), Regal O-O (oxyfluorfen 2% plus oxadiazon 1%, 3.36 kg ai/ha), OH2 (oxyfluorfen 2% plus pendimethalin 1%, 3.36 kg ai/ha), Corral (pendimethalin 2.68%, 2.24 kg ai/ha), and Pendulum 2G (pendimethalin 2%, 2.24 kg ai/ha) did not injure *Hydrangea macrophylla* and all treatments had greater than 94% weed control. Injury was induced by increasing the rate two and three times. However, no significant differences were observed after 14 days after application and hydrangea growth was not affected (Conwell et al. 2002). In addition, pendimethalin at 3.4 kg ai/ha or pendimethalin plus oxyfluorfen at 3.4 kg ai/ha or 6.7 kg ai/ha applied prior

to simulated shipping in an enclosed environment did not injure Japanese Barberry (*Berberis thunbergii* DC var. *atropurpurea* 'Crimson Pygmy') (Hubbard et al. 1992).

'Mary Nell' holly [*Ilex cornuta* "Burfordii" x *I. pernyi* 'Red Delight') x *I. latifolia*] was not injured by pendimethalin, oryzalin, oxyfluorfen, isoxaben and simazine more than 10%. Norflurazon produced temporary discoloration of the older foliage. Growth indices were not influenced by any herbicide treatment (Reeder et al. 1994). Similar results were obtained by Derr et al. (1996), when he found that plant size of holly (*Ilex aquifolium* L. x *Ilex cornuta* Lindl.) treated twice annually with oryzalin plus isoxaben over a two year period was not different from those treated with oryzalin plus simazine or oryzalin plus oxyfluorfen; however oryzalin, suppressed shoot growth of Chinese holly (*Ilex cornuta* Lindl.). In addition, Ruter et al. (1992) found that dinitroaniline herbicides such as oryzalin and pendimethalin reduced the root growth of 'Helleri' holly (*Ilex crenata* Thunb. 'Helleri'). *Ilex cornuta* Lindl. and Prax. 'Needle point' holly was injured by the three formulations but injury was greater with the granular formulation of prodiamine at 1.68 kg ai/ha (Briggs and Whitwell 2002).

Isoxaben at 1.1 kg/ha did not reduce shoot fresh weight of *Rhododendron* spp, but reduced shoot fresh weight of English ivy (*Hedera helix* L.) and common lilac (*Syringa vulgaris* L.) (Derr and Salihu 1996).

Azalea (*Rhododendron indicum* x 'Macrantha Orange') was susceptible to imazaquin, imazapic, and imazethaphyr, which caused chlorosis, leaf tip necrosis, and loss of apical dominance. Even though azaleas treated with these herbicides produced more flowers, those were slightly discolored and smaller. In addition, the imidazolinones

reduced juniper growth 17 to 35%, but they did not reduce liriop growth 4 WAT. The only taxa tolerant of imazethapyr was French marigold (Hurt and Vencill 1994b).

Ornamental plant tolerance to herbicides depends on many factors, but one of the most important factors is plant genetics. In the experiment we evaluated crop injury and growth distortion in response to selected herbicides. This information will provide growers new managerial practices for weed control in ornamental production, therefore less MB dependency to achieve their weed control objective.

MATERIALS AND METHODS

Ten ornamental species: Japanese Barberry (*Berberis thunbergii* 'Burgundy Carousel'); Redosier Dogwood (*Cornus stolonifera* 'Alleman's Compact'); Winged Euonymus (*Euonymus alatus* 'Chicago Fire'); Panicle Hydrangea (*Hydrangea paniculata* 'Kyushu'); Holly 'Blue Prince' (*Ilex* x 'Blue Prince'); White Spruce (*Picea glauca* 'Dwarf Alberta'); Japanese Spirea (*Spiraea japonica* 'Fire Light'); Preston Lilac (*Syringa* x *prestoniae* 'Donald Wyman'); Anlojap Yew (*Taxus media* 'Browni'); and White Cedar (*Thuja occidentalis* 'Holmstrup') were planted at the Horticulture Research and Teaching Center located near East Lansing, MI.

All these plants belong to the class Magnoliopsida except for *Thuja occidentalis*, *Taxus media*, and *Picea glauca* which belong to Pinopsida class.

The soil type was a clay loam with a range of 28 to 42% sand, 28 to 36% silt and 30 to 36% clay, and pH ranging from 6.5 to 7.1. P, Mg and K were not limiting factors. The plant materials were obtained from a local nursery.

The plants were planted on June 30 and July 1, 2003 using a mechanical transplanter. Each replication had 10 rows and each row was planted with one species. The species order in each replication was randomly assigned. Distance between plants was 30 cm with 120 cm between rows and the row length was 40 m. The first quarter (10 m) of the row was used to set up the plots; the last quarter of each row was reserved for the next year (2004) experiment. Herbicide plots were arranged perpendicular to the plant rows and they were 1.5 m wide and 11 m long and each plot crossed the ten ornamental species.

For the crop evaluation (injury and size index) a split block design with 4 replications was used, being treatments the main plot and species the subplot. Weed control evaluation was analyzed as a randomized complete block design.

Terbacil (1.12 kg ai/ha), imazapic (0.07 kg ai/ha), imazaquin (0.42 kg ai/ha), halosulfuron (0.035 kg ai/ha), flumioxazin granular (0.28 kg ai/ha), isoxaben (1.12 kg ai/ha) plus trifluralin (0.84 kg ai/ha) were applied over the top of the plants on July 14, 2003. An untreated plot was left as a control. Herbicides were applied using a CO₂ backpack sprayer with a two nozzle boom (FF 11002, Teejet® nozzle, Spraying Systems Co, Wheaton, Illinois) at 207 kPa with 187 L/ha output. Flumioxazin granular was applied manually with a shaker. After planting, plots were irrigated to incorporate the herbicides into the soil. At the application time air temperature was 26 C, relative humidity 43%, 15% cloudy; soil was dry and soil temperature was 26 C.

At application, a few common lambsquarters, 1 to 3 cm, and redroot pigweed, 1 to 4 cm height were present.

Ornamental injury and weed control were evaluated on July 22, July 29, August 4 and August 28, 2003. Plant injury was rated from 1 to 10; with 1 indicating no injury and 10 indicating a dead plant. Chlorosis, necrosis, and malformation or distorted growth and the degree of those symptoms were the parameters used to evaluate injury.

Weed control was rated visually from 1 to 10, with 1 indicating no control and 10 indicating 100% control. Weed control was evaluated for each weed species present in the control plot.

Plant size index was measured on November 14, 2003 and June 3, 2004 and was calculated by using the following formula: $(\text{height} + \text{width})/2$. Three plants from each species were measured, and the average of those three was used for the statistical analysis.

In 2004, plants at the opposite end of the row were used for the experiment. All procedures were the same as 2003. Weeds were pulled within the row on June 3 and weeds between rows were mechanically removed. Plots were sprayed with the corresponding treatments on June 25. Air temperature was 19 C, wind speed 11 km/h, soil temperature 23 C and 10% cloudy at time of application.

Weeds within the rows were hand-weeded frequently in order to prevent competition with plants. Plant injury was evaluated on July 9, July 23, August 5, 2004, and weed control was evaluated on August 5, and August 20, 2004. Size index was measured on November 12, 2004.

RESULTS AND DISCUSSION

If the herbicide by year interaction was significant, mean separation was done for each year; if not significant, means were pooled across years. For statistical analysis, the 2 and 6 week after treatment (WAT) evaluations for each year are presented.

Herbicides did not cause injury on *Ilex* 'Blue Prince', *Picea glauca*, *Taxus media*, and *Thuja occidentalis* at 2 WAT except for terbacil and flumioxazin which produced 2.3 injury on *Ilex* 'Blue Prince' in 2004 and for imazapic and halosulfuron which injured 2.0 and 2.8 *Taxus* in 2004; however these treatments were safe in 2003 (Table 1).

Furthermore, *Ilex* 'Blue Prince', *Picea glauca*, *Taxus media*, and *Thuja occidentalis* were not injured by any treatment at 6 WAT in either year (Table 2). That agrees with McDaniel et al. (1999), who found that 'Blue Girl' holly (*Ilex x meserveae* S.Y. Hu 'Blue girl') was tolerant of halosulfuron. Altland et al. (2003) also found that China girl holly (*Ilex x meserveae* S.Y. Hu 'China girl') was tolerant to halosulfuron, imazaquin or isoxaben; however, imazaquin visibly injured Japanese holly (*Ilex crenata* 'Compacta') but not Burford holly (*Ilex cornuta* 'Burfordii').

In our research, the woody ornamentals *Ilex* 'Blue Prince', *Picea glauca*, *Taxus media*, and *Thuja occidentalis* were the most tolerant plants. Derr et al. (1993) suggested that chlorimuron had greater potential in woody ornamentals. In addition, Wooten et al. (2001) found that flumioxazin was safer on woody ornamentals, *Ilex* x 'Nellie R. Stevens', *Ilex crenata* 'Green Luster', and *Thuja occidentalis* 'Emerald', rather than in herbaceous plant *Spiraea* x 'Goldmound'.

Terbacil at 1.12 kg ai/ha caused the most injury to all species evaluated at 2 and 6 WAT for both years, except for *Syringa x prestoniae* which was not injured in 2003, but

had 5.8 injury in 2004 at 6 WAT, and for *Euonymous alatus* which was not injured at 2 WAT, but had 4.5 injury at 6 WAT.

Imazaquin, imazapic, and halosulfuron had similar injury effect. At 2 WAT these treatments caused injuries on *Berberis thunbergii*, and *Cornus stolonifera* in both years, and *Hydrangea paniculata* in 2004. At 6 WAT, injury rates were higher in these species except for halosulfuron which was not different from the control in *Berberis thunbergii* in 2004 and *Hydrangea paniculata* in both years. Imazaquin and halosulfuron injured slightly *Syringa x prestoniae*, with ratings of 2.5 and 2.8, respectively in 2004, but not in 2003. In addition imazaquin and imazapic injured *Spiraea japonica* 3.1 and 3.5, respectively.

Flumioxazin was one of the safest herbicides in all the crop species. Even though some injuries were observed in *Hydrangea* in 2004 and *Spiraea* in both years at 2WAT, when evaluated at 6 WAT none of the treatments were different from the control.

Isoxaben plus trifluralin was the safest treatment. It did not cause injury in any of the species evaluated at 2 and 6 WAT.

Euonymous alatus did not show injury in our study; however, Derr et al. (1996) reported 20 to 30 % injury with isoxaben to *Euonymous alatus* (Thunb) Sieb. 'Compacta', but only slight reductions in root and shoot weight. This treatment was safe on *Hydrangea paniculata*. Similar results were reported by Conwell et al. (2002) with *Hydrangea macrophylla*.

Plant size index analysis is shown in Table 3. Measurements taken in November, 2003 and 2004 were used for the statistical analysis. Since interaction of species by year was significant in *Cornus stolonifera*, data for this species is presented by year. Treatments applied to all species did not have any differences compared to the control

except for *Cornus stolonifera* and *Spiraea japonica*. None of the treatments were different ($P \leq 0.05$) from the control in *Spiraea japonica*. Treatments applied to *Cornus stolonifera* were not different from the control in 2003; but in 2004, imazaquin and imazapic treatments resulted in the smallest plants, and plants treated with flumioxazin resulted in the largest plants. As mentioned previously, injury produced to *Cornus stolonifera* by imazaquin and imazapic reduced growth and resulted in the smallest plants.

Weed control ratings are presented in Tables 4 for 2 WAT and 5 for 6 WAT. Terbacil had the best broadleaf weed control at 2 and 6 WAT. Imazaquin and flumioxazin effectiveness was comparable to terbacil at 6 WAT, with some exceptions. Imazaquin did not control common lambsquarters in 2003 and flumioxazin was less effective in controlling common lambsquarters in 2003, and common groundsel and common chickweed in 2004.

Imazapic gave poor redroot pigweed and common lambsquarters control in 2003, but gave good control in 2004. Imazapic controlled all weeds evaluated within a range of 8.3 to 9.8, and had acceptable control of common purslane (7.5) and common groundsel (6.3) at 6 WAT.

Halosulfuron provided variable weed control among weed species. It had the best control of common groundsel, curly dock, and redroot pigweed in 2004 at 6 WAT; however, it gave fair control (3.0 to 8.3) of the rest of the species evaluated.

Isoxaben plus trifluralin gave good weed control at 2 WAT, except for common mallow (4.0). Redroot pigweed and common lambsquarters control was fair (7.0) at 2 WAT in 2003, but weed control was one of the highest at 6 WAT in 2004. Isoxaben plus

trifluralin had poor control of dandelion (4.0), but controlled eastern black nightshade, common purslane, common groundsel, common chickweed, and curly dock within a range of 7.2 to 8.8.

Terbacil, imazaquin, and imazapic had the best grass control in all species evaluated except for imazapic, which gave only fair control of annual bluegrass at 2 and 6 WAT (Table 6). In general, halosulfuron, flumioxazin, and isoxaben plus trifluralin provided poor grass control. However, flumioxazin and isoxaben plus trifluralin provided 10 and 7.8 control of witchgrass at 6 WAT, respectively.

CONCLUSIONS

Herbicide tolerance was clearly different among species. Herbicides applied were safe to woody ornamentals belonging to the Pinopsida class: *Ilex*, *Picea glauca*, *Thuja occidentalis*, and *Taxus media*. Size index (plant growth) was not affected by any of the treatments in these species.

Terbacil was one of the best treatments for weed control but injured most of the crop species evaluated. Even though those injuries were not reflected in the size index, injuries were severe and would affect plant marketability.

In general, the higher weed control the higher injury observed on crops; however, flumioxazin and isoxaben plus trifluralin were the safest herbicides and they had a relatively high weed control.

Crop injury and weed control was variable among years. More specific, injuries were different between years in *Berberis thunbergii*, *Cornus stolonifera*, and *Syringa x prestoniae*, and weed control was different in common lambsquarters and redroot

pigweed. More knowledge about herbicide variability between years is required in order to improve safety of herbicide application in ornamentals.

Herbicides tested have the potential to effectively control weeds in the ornamental plants evaluated, and they have the potential to replace MB application when used for weed control purposes. Herbicide combinations, application methods, formulations, and rate of application are areas where research is required in order to achieve a higher crop safety and a wider weed control spectrum.

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Table 1. Ornamental plant injury 2 weeks after preemergence herbicide application.¹

Treatment	Rate	Berberis	Cornus	Euony.	Hydrangea		Ilex		Picea	Spirea	Syringa	Taxus	Thuja
Kg ai/ha		2003		2004		2003		2004		2003		2004	
-----Injury ratings ² -----													
Terbacil	1.12	7.0 a	7.0 a	2.1 a	5.0 a	8.3 a	1.0 a	2.3 a	1.1 a	3.5 a	5.5 a	1.2 a	1.3 a
Imazaquin	0.42	3.1 b	2.4 b	2.1 a	2.0 b	2.5 b	1.0 a	1.3 bc	1.0 a	1.9 bc	1.5 b	1.2 a	1.0 a
Imazapic	0.07	2.9 bc	2.5 b	1.9 a	1.3 b	2.3 b	1.0 a	1.6 abc	1.0 a	1.6 bc	1.7 b	1.0 a	1.1 a
Halosulfuron	0.035	2.6 bc	2.8 b	1.9 a	1.3 b	2.8 b	1.0 a	1.3 bc	1.0 a	1.5 bc	1.7 b	1.0 a	1.2 a
Flumioxazin	0.28	2.0 bcd	1.1 c	1.9 a	1.3 b	2.0 b	1.0 a	2.3 a	1.0 a	2.1 b	1.6 b	1.2 a	1.0 a
Isoxaben +	1.12 +												
Trifluralin	0.84	1.7 cd	1.8 cb	1.5 a	1.3 b	1.0 c	1.0 a	1.0 c	1.0 a	1.5 bc	1.9 b	1.0 a	1.0 a
Untreated	--	1.0 d	1.0 c	1.0 a	1.0 b	1.0 c	1.0 a	1.0 c	1.0 a	1.0 c	1.0 b	1.0 a	1.0 a

¹ Means within a column with the same letter are not significantly different at P=0.05

² Injury was graded from 1 to 10 scale (1= no injury, 10= dead plant)

If year not specified, crop injury by year interaction not significant (P>0.05) and means were pooled across years.

Table 2. Ornamental plant injury at 6 weeks after preemergence herbicide application.¹

Treatment	Rate	Berberis		Cornus		Euony.		Hydrangea		Ilex		Picea		Spirea		Syringa		Taxus	Thuja
	kg ai/ha	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004		
Injury ratings																			
Terbacil	1.12	9.7 a	7.3 a	6.3 a	4.8 b	4.5 a	5.2 a	1.4 a	1.1 a	3.7 a	2.0 a	5.8 a	1.8 a	1.0 a					
Imazaquin	0.42	8.5 ab	3.3 b	4.8 a	8.3 a	1.9 bc	4.2 ab	1.6 a	1.1 a	3.1 ab	1.8 a	2.5 b	1.6 a	1.0 a					
Imazapic	0.07	7.0 ab	3.3 b	4.3 ab	8.0 a	1.9 bc	3.9 b	1.1 a	1.0 a	3.5 a	2.5 a	2.0 bc	1.4 a	1.0 a					
Halosulfuron	0.035	6.5 bc	1.7 bc	4.0 abc	7.7 a	1.9 bc	1.7 c	1.1 a	1.0 a	2.1 bc	1.5 a	2.8 b	1.4 a	1.0 a					
Flumioxazin	0.28	3.2 d	1.5 c	1.8 cd	1.0 c	1.5 bc	1.3 c	1.1 a	1.0 a	2.1 bc	1.3 a	1.8 bc	1.0 a	1.0 a					
Isoxaben +	1.12																		
trifluralin	0.84	3.7 cd	2.2 bc	2.3 bcd	1.7 c	2.0 b	1.5 c	1.2 a	1.0 a	2.0 bc	1.3 a	1.8 bc	1.1 a	1.0 a					
Untreated	--	1.0 d	1.0 c	1.0 d	1.0 c	1.0 c	1.0 c	1.0 a	1.0 a	1.0 c	1.0 a	1.0 c	1.0 a	1.0 a					

¹ Means within a column with the same letter are not significantly different at P=0.05. Injury was graded from 1 to 10 scale (1= no injury, 10= dead plant).

If year not specified, crop injury by year interaction not significant (P>0.05) and means were pooled across years.

Table 3. Plant size index taken on November 2003 and 2004.¹

Treatment	rate	Berberis	Cornus ²	Euony.	Hydrangea	Ilex	Picea	Spirea	Syringa	Taxus	Thuja
kg ai/ha		2003	2004	----- cm -----							
Terbacil	1.12	28.3 a	12.4 a	34.2 bc	24.7 a	21.0 a	14.4 a	25.2 a	24.5 ab	12.1 a	22.9 a
Imazaquin	0.42	26.0 a	11.5 a	25.4 d	23.3 a	20.1 a	12.4 a	24.1 a	22.2 b	11.8 a	20.7 a
Imazapic	0.07	25.2 a	13.3 a	24.4 d	21.5 a	19.2 a	12.1 a	23.2 a	21.5 b	11.8 a	21.1 a
Halosulfuron	0.035	28.2 a	12.8 a	28.1 dc	24.1 a	23.8 a	13.8 a	23.3 a	24.1 ab	12.5 a	22.3 a
Flumioxazin	0.28	30.7 a	17.0 a	50.4 a	23.2 a	21.3 a	14.3 a	23.0 a	26.7 a	11.2 a	22.4 a
Isoxaben	+ 1.12 +										
trifluralin	0.84	27.5 a	14.1 a	38.2 b	23.4 a	23.2 a	13.9 a	23.6 a	25.5 a	11.5 a	20.4 a
Untreated	--	32.2 a	15.5 a	34.6 bc	23.1 a	23.7 a	15.9 a	23.1 a	23.8 ab	11.8 a	19.9 a

¹ Means within a column with the same letter are not significantly different at P=0.05. Plant size index was calculated using the following formula: (height + width)/2

² Data for *Cornus stolonifera* is presented by year due to presence of species by year interaction.

Table 4. Weed control at 2 weeks after treatment.¹

Treatment	Rate	AMARE	MALNE	CHEAL	POROL ²	SENVU	SOLPT	STEME
	kg ai/ha	2003	2003	2003	2004	2004	2004	2004
----- Control ratings -----								
Terbacil	1.12	8.0 a	5.0 a	9.0 a	10 a	9.4 a	10 a	10 a
Imazaquin	0.42	8.0 ab	5.0 a	7.0 bc	10 a	8.0 ab	10 a	10 a
Imazapic	0.07	7.0 ab	5.0 a	5.0 cd	9.5 a	6.6 b	5 c	10 a
Halosulfuron	0.035	5.0 c	5.0 a	4.0 d	9.8 a	4.7 c	10 a	5.8 b
Flumioxazin	0.28	7.0 b	5.0 a	7.0 b	9.5 a	9.1 a	9.8 a	10 a
Isoxaben + 1.12 +								8 b
trifluralin	0.84	7.0 ab	4.0 a	7.0 bc	9.5 a	8.1 ab	7.3 b	10 a
Untreated	--	1.0 d	1.0 b	1.0 e	1.0 b	1.0 d	1.0 d	1.0 c

¹ Means within a column with the same letter are not significantly different at P=0.05. Weed control was graded using a 1 to 10 scale (1= no weed control, 10= complete weed control)

² POROL had no herbicide by year interaction and data was pooled across years. CHEAL had interaction. AMARE and MALNE were evaluated in 2003 while SENVU, SOLPT and STEME were evaluated in 2004.
Weeds listed: AMARE= redroot pigweed, MALNE= common mallow, CHEAL= common lambsquarters, SOLPT= eastern black nightshade, POROL= common purslane, SENVU= groundsel, STEME= common chickweed.

Table 5. Weed control at 6 weeks after treatment. ¹

Treatment	Rate	AMARE ²		MALNE		CHEAL		SOLPT		POROL		SENVU		STEME		TAROF		RUMCR	
	kg ai/ha	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
----- Control ratings -----																			
Terbacil	1.12	9.0 a	9.8 ab	9.9 a	10 a	10 a	10 a	10 a	10 a	9.9 a	9.9 a	9.5 a	10 a	10 a	10 a	7.0 ab	10 a	10 a	10 a
Imazaquin	0.42	9.0 a	10 a	9.5 ab	4.0 c	10 a	10 a	9.4 a	8.5 abc	9.8 a	10 a	9.8 a	10 a	10 a	10 a	10 a	9.5 ab	10 a	9.5 ab
Imazapic	0.07	7.0 b	10 a	9.8 a	4.0 c	8.8 b	9.5 a	9.5 a	7.5 bc	6.3 c	9.5 a	9.5 a	9.5 a	9.5 a	9.5 a	9.0 a	8.3 b	9.5 a	8.3 b
Halosulfuron	0.035	6.0 b	10 a	7.5 cb	3.0 c	8.3 b	4.5 c	4.5 c	6.1 c	9.8 a	9.8 a	9.8 a	9.8 a	6.8 bc	5.0 bc	5.0 bc	9.0 ab	9.8 a	9.0 ab
Flumioxazin	0.28	9.0 a	7.5 b	9.6 a	7.0 b	9.3 ab	9.8 a	9.8 a	9.2 ab	7.8 b	7.8 b	7.8 b	7.8 b	6.3 c	8.0 ab	8.0 ab	9.8 a	9.8 a	9.8 a
Isoxaben +	1.12 +																		
trifluralin	0.84	6.0 b	9.5 ab	7.3 c	4.0 c	9.3 ab	7.6 b	7.6 b	7.2 bc	8.0 b	8.0 b	8.0 b	8.0 b	8.5 ab	4.0 bc	4.0 bc	8.8 ab	8.8 ab	8.8 ab
Untreated	--	1.0 c	1.0 c	1.0 d	1.0 d	1.0 c	1.0 d	1.0 d	1.0 d	1.0 d	1.0 d	1.0 d	1.0 d	1.0 d	1.0 c	1.0 c	1.0 c	1.0 c	1.0 c

¹ Means within a column with the same letter are not significantly different at P=0.05

Weed control was graded using a 1 to 10 scale (1= no weed control, 10= complete weed control)

² AMARE and CHEAL control ratings are presented by year due to herbicide by year interaction. STEME and RUMCR were evaluated in 2004 and TAROF only in 2003. If year not indicated, then interaction herbicide by year was not significant.

Weed listed: AMARE= redroot pigweed, MALNE= common mallow, CHEAL= common lambsquarters, SOLPT= eastern black nightshade, POROL= common purslane, SENVU= groundsel, STEME= common chickweed, TAROF= curly dock

Table 6. Grass species control for the 2004 study at 2 and 6 weeks after preemergence application. ¹

Treatment	Rate	POAAN ²	PANCA	POAPR	ECHCG	POAAN	POAPR	PANCA	DIGIS
kg ai/ha		-----2 weeks-----				-----6 weeks-----			
----- Control ratings -----									
Terbacil	1.12	10 a	10 a	10 a	10 a	10 a	9.8 a	10 a	10 a
Imazaquin	0.42	9.0 a	10 a	9.5 a	10 a	7.8 ab	9.3 a	10 a	9.0 ab
Imazapic	0.07	5.0 b	9.3 a	8.5 ab	8.8 a	5.5 bc	8.0 ab	8.8 a	8.0 abc
Halosulfuron	0.035	4.8 b	7.3 b	6.8 c	8.8 a	4.5 c	4.5 c	4.5 b	6.8 bc
Flumioxazin	0.28	6.8 b	9.8 a	7.5 bc	10 a	7.0 b	7.3 b	10 a	7.0 bc
Isoxaben	+ 1.12	+							
trifluralin	0.84	4.8 b	9.5 a	7.0 bc	10 a	3.5 c	6.5 b	7.8 a	5.8 c
Untreated	--	1.0 c	1.0 c	1.0 d	1.0 b	1.0 d	1.0 d	1.0 c	1.0 d

¹ Means within a column with the same letter are not significantly different at P=0.05. Weed control was graded using a 1 to 10 scale (1= no weed control, 10= complete weed control)

² POAAN= Annual bluegrass, PANCA= witchgrass, POAPR= Kentucky bluegrass, ECHCG= Barnyardgrass, DIGIS= large crabgrass

**CHAPTER V: RESPONSE OF FIELD AND CONTAINER-GROWN CONIFERS
SEEDLINGS TO HERBICIDES**

INTRODUCTION

The Christmas tree and short rotation woody crop industries in the United States include almost 15,000 farmers. This industry sold \$400 million of products in 2002. In Michigan there were 1,076 growers in 2002, which represents 7% of the total United States growers, and their sales reached \$31 million in 2002 (Anonymous 2002).

California, Florida, Michigan, Oregon, Pennsylvania, and Texas are the major producing states of nursery and floriculture crops (Anonymous 2004).

Methyl bromide (MB) is a fumigant extensively used to control a broad spectrum of soil diseases. The woody ornamental seedling industry uses MB for fungi, weed, and nematode control, applying it to 75% of their acreage (Bird 2004).

MB is an efficient fumigant to help achieve high yields and good quality; however, its use in field applications will be banned at the end of 2005. Bromine, which is one of the atoms present in the MB molecule, degrades ozone molecules in the stratosphere. The ozone layer protects the earth from incoming UV light. As a consequence of the ozone degradation, more UV radiation hits the earth, which causes human skin cancer or cataracts, and also may contribute to global warming (Miller 1996).

The MB phase out will limit weed control tools available for the conifer industry. As a consequence herbicides will become more important for weed control.

Growers in the major producing states of nursery and floriculture crops applied 2.16 million kg of pesticide active ingredients in 2003. Herbicides accounted for 20% (0.44 million kg) of the total pesticide use. Coniferous evergreens, Christmas trees, and deciduous shrubs account for 39% of the 0.44 million kg. The most commonly used

herbicides in this industry are glyphosate (26%), oxyfluorfen (8%), and oryzalin (6%) (Anonymous 2004).

Shape, density, and height are the main factors in tree choice when consumers are selecting a Christmas tree (Florkowski et al. 1992). Chemical weed control plays an important role in achieving those desired characteristics. Christmas tree qualities, such as foliage density and tree weight generally improved with more frequent herbicide application. Furthermore, Colorado spruce (*Picea pungens*), Douglas fir (*Pseudotsuga menziesii*), and Fraser fir (*Abies fraseri*) benefited more by the higher frequency of herbicide application than Scots or white pine (*Pinus sylvestris*, *Pinus strobus*) (Brown et al. 1989). In addition, herbicides reduced weed competition and improved first-year growth, and most of the species evaluated, including eastern white pine, showed a significant growth benefit from weed control (Seifert and Woeste 2002). Furthermore, Norway spruce growth during the late part of the growing season was increased by glyphosate application and fertilization treatment; however, allocation of growth to roots was highest in the herbicide treatment with glyphosate and lowest for the fertilization treatment (Nilsson and Orlander 2003).

Weed control practices can greatly influence feeding damage to roots by grubs (e.g. *Phyllophaga spp* and *Polyphylla spp*), thus influencing wood volume and tree health. Tree plots treated entirely and in strips with herbicide contained the healthiest, least damaged trees with the highest wood volume, while supporting the lowest mean grub densities, 14 and 22 grubs per m², respectively. On the other hand, mowed sod plots supported the densest grub populations and contained trees with the most severe root damage, lowest wood volume and poorest health (Kard and Hain 1987).

The application of molecular biology techniques such as genetic engineering has resulted in significant gains in many agricultural crops. Traits such as herbicide resistance have the potential to reduce weed control cost, particularly in high density plantations. Furthermore, Bishop-Hurley et al. reported transgenic conifers, *Pinus radiata* (D. Don) and *Picea abies* (Karst) to be resistant to glufosinate.

Timing of application during the crop growing season, herbicide rate and part of the plant sprayed can greatly affect crop injury and severity. Metribuzin at 1.12 kg/ha and hexazinone at 2.0 kg/ha applied in early spring and directed to hit the lower part of dormant trees caused unacceptable injury to white pine (*Pinus strobus*) but the herbicides were tolerated at half rate. Late season applications of glyphosate at 1.1 or 2.2 kg/ha, triclopyr ester at 1.1 or 2.2 kg/ha and dichlorprop at 2.2 kg/ha caused only minor injury to fraser fir (*Abies fraseri*), balsam fir (*A. balsamea*) and white spruce (*Picea glauca*). In addition, glyphosate controlled a broad spectrum of perennial weeds and brush, including *Rubus sp.* On the other hand, white pine and Douglas fir (*Pseudotsuga menziesii*) were more sensitive to triclopyr and glyphosate in autumn (Ahrens and Dwyer 1982).

Herbicide selectivity not only depends on herbicide active ingredient uptake, translocation and metabolism, but also depends on plant morphology and physiology. McNeil et al. (1984) found that foliar accumulation of ¹⁴C-hexazinone varied between tree species, being higher in loblolly pine, then in bur oak, then in black walnut and eastern red cedar, whereas tebuthiuron foliar concentration was higher in bur oak, then loblolly pine, then eastern red cedar and black walnut. Furthermore, the presence of hexazinone metabolites in loblolly pine suggest that it may be resistant to this herbicide as a result of its ability to degrade hexazinone (McNeil et al. 1984). However, Jensen et

al. (1990) found that hexazinone metabolism was similar in bristly dewberry (*Rubus-hispidus* L.) and black chokeberry (*Pyrus melanocarpa*) and the difference in concentration was because of a higher root:foliage (weight) ratio in black chokeberry. Green et al. (1992) found that Loblolly pine (*Pinus taeda* L.) and yaupon (*Ilex vomitoria* (L.) Ait.) absorbed significantly less glyphosate than red maple (*Acer rubrum* L.) or white oak (*Quercus alba* L.) and white oak accumulated more glyphosate in the roots compared to red maple.

Preemergence application was more effective than postemergence application to control weeds grown from seeds. Isoxaben applied preemergence provided very good control of all weed species evaluated. However, applied postemergence, it was ineffective against many weed species tested. The activity of preemergence herbicides in containers was greater than in field situations, and the earliest application dates had the best weed control (Dixon and Clay 2004).

Our objective was to compare and evaluate herbicide tolerance and weed control efficiency in seven species of conifers grown in field and containers. This research will provide Christmas tree growers with information that will improve weed control practices and allow growers to be less dependent on MB.

MATERIALS AND METHODS

Herbicide evaluation in seedlings grown in field

2003 experiment

Douglas Fir (DF) – (*Pseudotsuga menziesii*), Black Hills Spruce (BHS) – (*Picea glauca* 'densata'), White Spruce (WS) – (*Picea glauca*), Colorado Blue Spruce (CBS) –

(*Picea pungens glauca*), Eastern White Pine (EWP) – (*Pinus strobus*) were planted at the Horticulture Teaching and Research Center located near East Lansing, MI on June 24, 2003. Tree species and height for the field and container experiment are shown in Table 1. The plant material was provided by Van's Pine nursery, West Olive, MI. Tree roots were trimmed and moistened with wet paper and trees were stored at 3 C for 1 to 3 days until planted.

Replications 1 and 2 of the experimental site were on a Marlette fine sandy loam, 2 to 6% slope that has moderately slow permeability. The third replication was on Colwood-Brookston loams that is poorly drained.

A randomized complete block design was used as a model for the statistical analysis with 3 replications. Trees were machine planted on June 24, 2003. Each replication had one row of each seedling species. The species order among replications and treatments within replication were assigned randomly. The rows for one replication were 25 m long and trees were planted 60 cm apart and rows were 3 m apart. Plots were set across the species row and they were 12 m long and 3 m wide, corresponding to 5 trees of each species. A 1.5 m aisle between plots and a 3 m aisle between replications were left to separate treatments.

Terbacil (1.12 kg ai/ha), imazaquin (0.42 kg ai/ha), flumioxazin granular (0.28 kg ai/ha), isoxaben (1.12 kg ai/ha) plus trifluralin (0.84 kg ai/ha), mesotrione (0.28 kg ai/ha), trifloxysulfuron (0.01 kg ai/ha) were applied on July 16, 2003. An untreated plot was left for comparison. A rototiller was passed through to eliminate weeds between rows the day of herbicide application. However, a few weeds were present within rows, where the rototiller could not reach. These included common lambsquarters 2-8 cm, eastern black

night shade 2-4 cm, common purslane 2-8 cm diameter and redroot pigweed 2-8 cm height.

Herbicides were applied using a CO₂ backpack sprayer with a four nozzle boom (8002 EVS nozzle) at 207 kPa with 187 L/ha output. Herbicides were sprayed over the top of the trees at an elevation of 50-60 cm and the spray orientation was along with the tree row. The theoretical coverage strip was 2.2 m leaving a small strip between rows that was not covered by the application. Flumioxazin granular was spread with a shaker. After application, the field was irrigated to incorporate the herbicides into the soil. At application time air temperature was 27 C, relative humidity 36%, 10% cloudy; soil was dry and soil temperature was 27 C.

Weed control and tree injury were graded on July 28, August 4, August 11, and August 28, 2003. Weed control was visually evaluated on a scale from 1 to 10, meaning 1 no weed control and 10 complete weed control. Tree injury was visually graded from 1 to 10, meaning 1 no injury and 10 dead tree.

Tree size index (growth index) was measured on October 30, 2003 and June 8, 2004. Size index of each tree was calculated by adding the highest and widest point and dividing by two (Briggs and Whitwell 2002). Five trees of each species were measured and the mean was used for statistical analysis. On the first date, dead trees were not considered to calculate the average; however, since dead trees could be caused by the herbicide effect, they were considered for the second measurement.

2004 experiment

For the second year experiment six conifer species were evaluated. Since white spruce and black hills spruce belong to the same genus and species, white spruce was deleted and replaced with Canaan fir (CA) – (*Abies balsamea* var. *phanerolepis*). Due to the importance of Fraser Fir (FF) – (*Abies fraseri*) for the Christmas tree industry, this species was added. Tree species and their height are shown in table 1.

The first row, which contained BHS in the replications 1 and 2 and EWP in the replication 3, was planted on May 13, 2004 and the rest of the rows were planted on June 9, 2004 due to weather conditions.

The experimental site was located adjacent to the 2003 experiment, sharing the same soil characteristics.

The same treatments as in 2003 were applied on June 18, 2004, including an untreated control. A rototiller was passed through 4 days before spraying to eliminate weeds between rows. In addition, no weeds were present at the application time, except for the first row, which was planted earlier and the rototiller could not be passed through. In that row, weeds were larger and grasses were the most predominant weeds.

Herbicide application was done as in 2003, except for pressure, which was 248 kPa. The higher pressure increased our output to 205 L/ha (9.6% more compared to 2003). At application time air temperature was 25 C, relative humidity 55%, cloud cover was 30% and wind speed was 4 km/h from the west; the soil was dry and 27 C.

Weed control and tree injury were rated on July 2, July 16, and July 28, 2004. Tree size was measured at planting and on November 11, 2004. Size index was calculated for both dates and the difference between dates was used for statistical analysis.

Herbicide evaluation in seedlings grown in containers

2003 experiment

Tree species and their height (cm) for both years are shown in the table 1.

Seedlings were planted in 12 L containers and placed on a gravel pad on June 17, 2003.

Soil used to fill pots was sandy loam. Long roots were trimmed off the seedlings before planting.

A randomized complete block design was used for the statistical analysis with 4 replications and 10 treatments. Each plot had 5 trees of each species and they were one meter apart. The order of species in each replication was randomized as well as the treatments.

Terbacil (1.12 kg ai/ha), imazaquin (0.42 kg ai/ha), flumioxazin (0.28 kg ai/ha), isoxaben (1.12 kg ai/ha) plus trifluralin (0.84 kg ai/ha), mesotrione (0.28 kg ai/ha), trifloxysulfuron (0.01 kg ai/ha), rimsulfuron (0.025 kg ai/ha), imazapic (0.070 kg ai/ha), and lactofen (0.28 kg ai/ha) were applied on July 18, 2003, and an untreated control plot was left for comparison. Herbicides were applied using a CO₂ backpack with a two nozzle boom (9502 EVS nozzle) at 207 kPa with 187 L/ha output. Treatments were sprayed over the top of the seedlings. Flumioxazin granular was applied using a manual shaker. Containers were watered after application. At application time air temperature was 24 C, relative humidity 59%, 15% cloudy and wind was 9 km/h from the NE. Soil in containers was moist.

Tree injury was graded as in the field experiment on July 25, August 6, August 12, and September 6, 2003. Weeds in containers were counted on August 12, and September 6, 2003. Tree size index was measured in October 30, 2003 and June 14, 2004 (Briggs and Whitwell 2002).

2004 experiment

For the second container experiment, sandy clay soil was used to fill containers. To prevent soil erosion, containers were filled first with 4 to 7 cm wood chips, and then soil was added to 3 cm below container top edge. Seedlings were planted on June 15, 2004.

Treatments and equipment were the same as in 2003. Herbicides were applied on June 24, 2004. At application time air temperature was 17 C, relative humidity 52% and wind speed 10 km/h from west.

Tree injury was graded on July 7, July 22, and August 5, 2004. Weeds species grown in the containers were counted on July 7, July 22, and August 5, 2004.

Tree size was measured at planting date and on November 11, 2004, the size index (growth index) was calculated for both dates and the difference between those was used for statistical analysis.

RESULTS AND DISCUSSION

Results analysis and interpretation were based on data collected at 2 and 6 weeks after treatment (WAT) for injury and weed control in both years and in both experiments. If herbicide by year interaction was not significant, the average for both years was considered for mean separation; if significant, data was presented for each year.

Field experiments

Tree injury of all species in all treatments was not different from the control at 2 WAT for both years, except for flumioxazin which slightly injured CBS (Table 2). In

addition, treatments applied to white spruce in 2003, and Canaan and Fraser fir in 2004 did not differ from the control.

There was no injury to CBS and EWP from any of the treatments at 6 WAT in both years and to WS in 2003. Terbacil application resulted in severe injury to BHS in both years, and to CA and FF in 2004 (4.8, 6.3, and 7.0 respectively). Injuries consisted of a generalized needle chlorosis and necrosis but more evident on the branch tips. The other treatments were not different from the control in BHS and CA. FF was injured 2.7 only by flumioxazin.

Douglas fir analysis resulted in herbicide by year interaction, thus results were separated by year (Table 3). In 2003 at 6 WAT, no treatment caused significant injury on DF. However, in 2004, terbacil and mesotrione caused significant injury. Mesotrione injuries consisted of needle discoloration (white needles), which is a particular characteristic of this pigment inhibitor herbicide. The higher rate (9.6% more) used in 2004 could be the reason for this increased injury in 2004.

Plant size index was not significant among treatments for all species on October 30, 2003 and on June 8, 2004 for the 2003 study.

In the 2004 experiment, size index taken in November 2004, was not significant for all species. However, when considering the size index difference between planting date and November 2004 (Table 4), FF and BHS had significant differences in injury among treatments. In both species terbacil resulted in the smallest difference, but only in BHS was the herbicide treatment significantly smaller than the control.

Terbacil, flumioxazin, mesotrione, imazaquin, and trifloxysulfuron had good control at 2 WAT on redroot pigweed (*Amaranthus retroflexus* L.) in both years and

common lambsquarters (*Chenopodium album* L.) in 2004 (Table 5). Common lambsquarters control in 2003 was poor with flumioxazin and trifloxysulfuron. All herbicides, except trifloxysulfuron, provided good eastern black nightshade (*Solanum ptychanthum* Dunal) control; also isoxaben plus trifluralin provided good control of this weed. The best common purslane (*Portulaca oleracea* L.) control was achieved with terbacil and flumioxazin, the rest provided control within a range 4.6 to 7.3. In addition, isoxaben plus trifluralin provided 4.3 and 4.0 control of redroot pigweed and common lambsquarter in 2003 respectively. None of the applications gave 100% grass control; the best treatments for grass control were trifloxysulfuron, imazaquin, terbacil, and mesotrione, which controlled grasses in a range of 7.1 to 8.5. In addition, all treatments provided good control of common mallow (*Malva neglecta* Wallr.) at 2 WAT.

Overall weed control at 6 WAT (Table 6) was similar to the control at 2 WAT. Terbacil, flumioxazin, mesotrione, and imazaquin gave good weed control on all weeds evaluated. However, flumioxazin had poor control of redroot pigweed and common lambsquarters in 2003, but these weeds were controlled almost 100% in 2004. Mesotrione had unacceptable common purslane control (4.0) and imazaquin had poor common lambsquarters control in 2003. Trifloxysulfuron and isoxaben plus trifluralin provided fair to poor control of common purslane in both years, and redroot pigweed, common lambsquarters, and common mallow in 2003. However trifloxysulfuron had excellent control of redroot pigweed and common lambsquarters in 2004, and isoxaben plus trifluralin provided good control over eastern black nightshade in both years and buckhorn plantain in 2004.

Flumioxazin, imazaquin, trifloxysulfuron and isoxaben plus trifluralin provided a higher control of redroot pigweed and common lambsquarters in 2004 than in 2003. These weeds were already emerged when the preemergence herbicides were applied in 2003. Dixon and Clay (2004) reported that the earlier the preemergence herbicide application, the better the weed control. Probably in our 2003 study, the presence of small weeds already emerged was enough to reduce their control for the next weeks.

At 6 WAT grass control was slightly reduced in all treatments. Terbacil, flumioxazin, imazaquin and trifloxysulfuron had the highest control (Table 6). Grass control by species was recorded in 2004 (Table 7). Species present in the plots were green foxtail (*Setaria viridis* (L.) Beauv.), witchgrass (*Panicum capillare* L.), large crabgrass (*Digitaria sanguinalis* (L.) Scop.), fall panicum (*Panicum dichotomiflorum* Michx.), yellow foxtail (*Setaria glauca* (L.) Beauv.), and barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.). Even though all treatments, except isoxaben plus trifluralin, had some grass control compared to the untreated control, none of them provided 100% control at 6 WAT.

Container experiment

Treatments applied to all species in both years did not result in any injury at 2 WAT (Table 8).

At 6 WAT (Table 9), terbacil had the highest injury rate in all species except for DF and WS in 2003. Furthermore, the other herbicides were not different from the control in DF, EWP, CA, FF and WS with some exceptions. Mesotrione injured DF, WS,

and FF 2.2, 3.0 and 1.7 respectively in 2004. Imazaquin slightly injured (1.7) FF in 2004, and lactofen injured EWP 3.8 both years.

Contrary to the field experiment, the container study resulted in severe injuries to BHS for all treatments at 6 WAT, except for trifloxysulfuron. In addition, flumioxazin, imazaquin, trifloxysulfuron, imazapic, and lactofen resulted in injuries on CBS compared to the control.

DF and WS analysis showed herbicide by year interaction, thus results were separated by year. These species were injured by terbacil and slightly less by mesotrione in 2004, but not in 2003.

In the 2003 container experiment, the size index taken in October 30, 2003 was not significantly different among treatments; however the measurement taken in June 14, 2004 showed differences in EWP and WS (data not shown). Seedlings treated with rimsulfuron resulted in the biggest EWP and the rest of the treatments were not different from control. In addition, none of the treatments were different from the control in WS. The container experiment in 2004 showed only significant differences among treatments in WS. However, when the difference in size index between July and November was analyzed, FF and CA became significant (Table 10). Terbacil had the lowest growth rate in those species. These growth reductions were in accordance with the plant injury observed in the terbacil plots.

Conclusions about weed control in the container (Table 11) are difficult to state due to the poor weed growth for some weed species in the control. However, terbacil, flumioxazin, mesotrione, and trifloxysulfuron provided good common lambsquarters control at 2 and 6 WAT in 2003 (data not shown). In 2004, all treatments provided good

control of redroot pigweed, carpetweed (*Mollugo verticillata* L.), and annual sowthistle (*Sonchus oleraceus* L.). Fall panicum was also controlled by all treatments, except for imazaquin and imazapic. Finally, black medic (*Medicago lupulina* L.) was controlled in all treatments except for imazaquin, isoxaben plus trifluralin, and imazapic.

CONCLUSIONS

Terbacil caused the most injury and gave the best weed control. In the field study, terbacil did not injure EWP and CBS in both years and WS in 2003 compared to the control, but produced severe injuries to BHS, DF in both years and CA and FF in 2004. The higher injury in 2004 may be explained by a higher rate (9% more) in that year. If this is the case, the optimum rate for weed control is very close to the rate that can be harmful to seedlings. Field research is required to determine if a lower rate of terbacil could still have good weed control and reduce plant injury.

All herbicides except terbacil may be safe to be used in all species evaluated, however environmental conditions year by year can influence the likelihood of injury.

Even though WS and BHS share the same genus and species; they differ in herbicide response. WS was more tolerant to herbicides than BHS. More field research is required to extend our knowledge in these species.

Plant size index was not in accordance with seedling injury observed in 2003. The growth in this period may have not been enough to detect statistical differences; however, for the field and container studies in 2004, when the size index difference was considered, thus analyzing only growth and taking out the individual tree size variability,

differences in growth were statistically detectable in the field and container study. Injury persistence was long enough to interfere with the normal growth.

Terbacil, flumioxazin, mesotrione, and imazaquin had an overall good weed control, controlling most weeds present in the field. In addition, trifloxysulfuron and isoxaben plus trifluralin had variable control among weed species being some times unacceptable.

Bare soil at application time improves weed control. Flumioxazin, trifloxysulfuron, imazaquin, and isoxaben plus trifluralin had better weed control when weeds were not present at the application time.

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Table 1. Tree species and tree height average used for the field and container studies in 2003 and 2004.

Tree species	2003	2004	
	Field & containers	Field	Containers
	----- cm -----		
Black Hills Spruce (BHS)	33	20	-- ¹
Eastern White Pine (EWP)	45	27	27
Colorado Blue Spruce (CBS)	40	20	20
Douglas Fir (DF)	22	30	30
White Spruce (WS)	50	--	20
Fraser Fir (FF)	--	17	17
Canaan (CA)	--	17	17

¹ Box without number indicates that this particular species was not evaluated for the study in this year.

Table 2. Conifer seedling injury in the field study at 2 weeks after treatment.¹

Treatment	Rate	BHS	CBS	DF	EWP	WS	CA	FF
Kg ai/ha		Injury Ratings -----						
		2003 2004 2004						
Terbacil	1.12	1.5	1.3	1.0	1.0	1.0	1.6	1.3
Flumioxazin ²	0.28	1.0	1.7	1.0	1.2	1.0	1.3	1.6
Mesotrione	0.28	1.0	1.3	1.0	1.2	1.3	1.6	1.0
Imazaquin	0.42	1.2	1.0	1.0	1.2	1.0	1.6	1.0
Trifloxysulfuron	0.01	1.2	1.2	1.0	1.0	1.0	1.3	1.3
Isoxaben+Trifluralin	1.12+0.84	1.0	1.2	1.0	1.3	1.0	1.3	1.0
Untreated	---	1.0	1.0	1.0	1.0	1.0	1.0	1.0
LSD (0.05)		NS	0.44	NS	NS	NS	NS	NS

¹ Abbreviation: NS, not significant. If no year is indicated the mean was pooled across 2003 and 2004.

Injury was graded from 1 to 10 scale (1= no injury, 10= dead plant)

² Flumioxazin produced slight injury to CBS, but not significant at 6 WAT

Table 3. Conifer seedling injury in the field experiment at 6 weeks after treatment.¹

Treatment	Rate	BHS	CBS	DF	EWP	WS	CA	FF
	Kg ai/ha	2003	2004	2003	2004	2003	2004	2004
----- Injury Ratings -----								
Terbacil	1.12	4.8	2.8	2.3	4.3	1.5	2.3	6.3
Flumioxazin	0.28	1.8	2.2	2.0	1.3	1.8	1.6	2.7
Mesotrione	0.28	2.2	2.0	1.3	3.3	1.5	1.3	3.3
Imazaquin	0.42	1.7	1.8	1.0	1.3	1.5	1.3	2.7
Trifloxysulfuron	0.01	1.8	2.0	1.7	2.0	1.5	1.3	1.3
Isoxaben+Trifluralin	1.12+0.84	1.3	2.2	1.7	1.7	1.3	1.3	1.3
Untreated	---	1.0	1.0	1.0	1.0	1.0	1.0	1.0
LSD (0.05)		1.66	NS	1.0	1.6	NS	NS	2.9
								1.1

¹ Abbreviation: NS, not significant. If no year is indicated the mean was pooled across 2003 and 2004.

Injury was graded from 1 to 10 scale (1= no injury, 10= dead plant)

Table 4. Size index difference in the field study for 2004.¹

Treatment	Rate	CBS	DF	FF	EWP	CA	BHS
	Kg ai/ha ----- cm -----						
Terbacil	1.12	1.36	1.83	-0.76	4.40	-1.53	- 0.50
Flumioxazin	0.28	3.36	3.86	0.13	4.06	1.46	0.93
Mesotrione	0.28	1.10	2.93	2.83	4.33	0.80	0.36
Imazaquin	0.42	3.30	3.06	3.20	3.66	0.40	1.26
Trifloxysulfuron	0.01	3.13	5.43	3.63	6.60	3.50	0.30
Isoxaben+Trifluralin	1.12+0.84	3.80	4.26	4.0	4.40	2.40	1.26
Control	---	3.63	4.00	1.73	4.70	0.83	0.70
LSD (0.05)		NS	NS	2.78	NS	NS	0.97

¹ Abbreviation: NS, not significant. Plant size index difference = plant size index (November) – plant size index (June)

Table 5. Weed control in the field study at 2 weeks after treatment.¹

Treatment	Rate	POROL	AMARE		CHEAL		SOLPT	GRASS	MALNE
	Kg ai/ha		2003	2004	2003	2004			2003
----- Control Ratings -----									
Terbacil	1.12	9.7	8.3	9.0	9.0	10	9.5	7.6	9.0
Flumioxazin	0.28	8.6	6.0	10	6.0	10	9.5	6.3	7.3
Mesotrione	0.28	4.6	8.3	10	9.0	10	9.5	7.1	9.0
Imazaquin	0.42	7.3	6.3	10	6.5	10	8.0	8.1	6.6
Trifloxysulfuron	0.01	6.3	6.0	9.6	5.0	9.6	3.2	8.5	8.0
Isoxaben+Trifluralin	1.12+0.84	6.3	4.3	8.6	4.0	9.0	9.2	4.3	6.6
Control	---	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
LSD (0.05)		2.0	3.0	1.3	2.8	1.3	2.0	2.2	2.5

¹ If no year is indicated the mean was pooled across 2003 and 2004. Weed control was graded using a 1 to 10 scale (1= no weed control, 10= complete weed control)

Weeds listed: AMARE= redroot pigweed, MALNE= common mallow, CHEAL= common lambsquarters, SOLPT= eastern black nightshade, POROL= common purslane..

Table 6. Weed control in the field study at 6 weeks after treatment.¹

Treatment	Rate	POROL ²	AMARE		CHEAL		SOLPT	MAINE	PLAMA	GRASS
	Kg ai/ha		2003	2004	2003	2004		2003	2004	
----- Control Ratings -----										
Terbacil	1.12	9.8	8.3	9.0	9.0	10	9.8	10	10	6.5
Flumioxazin	0.28	8.0	4.6	10	5.3	9.7	9.1	7.0	10	4.8
Mesotrione	0.28	4.0	10	10	10	9.7	10	10	10	4.5
Imazaquin	0.42	7.8	7.6	10	7.0	9.0	8.8	6.0	10	6.5
Trifloxysulfuron	0.01	6.3	7.0	10	5.0	9.7	3.1	4.0	4.0	7.5
Isoxaben+Trifluralin	1.12+0.84	4.6	6.3	7.0	5.6	8.7	8.3	5.0	10	3.3
Control	---	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
LSD (0.05)		3.1	3.1	1.4	2.9	0.95	1.7	5.0	1.9	2.9

¹ If no year is indicated the mean was pooled across 2003 and 2004. Weed control was graded using a 1 to 10 scale (1= no weed control,

10= complete weed control)

² POROL= common purslane, AMARE= redroot pigweed, CHEAL= common lambsquarters, SOLPT= eastern black nightshade, MALNE= common mallow, PLAMA= broadleaf plantain.

Table 7. Weed control in the field study in the Poaceae family in 2004 at 6 weeks after treatment.¹

Treatment	Rate	PANCA ²	DIGIS	PANDI	SETLU	ECHCG
	Kg ai/ha	Control Ratings (2004)				
Terbacil	1.12	6.0	8.3	7.7	5.7	8.3
Flumioxazin	0.28	5.0	6.3	4.0	6.7	6.7
Mesotrione	0.28	2.7	6.3	5.0	3.7	6.7
Imazaquin	0.42	8.3	3.7	5.0	4.3	7.0
Trifloxysulfuron	0.01	7.3	7.0	6.3	7.0	8.0
Isoxaben+Trifluralin	1.12+0.84	2.3	2.3	2.7	1.3	3.0
Control	---	1.0	1.0	1.0	1.0	1.0
LSD (0.05)		3.8	3.6	3.2	3.6	3.4

¹ Weed control was graded using a 1 to 10 scale (1= no weed control, 10= complete weed control)

² PANCA = witchgrass, DIGIS= large crabgrass, PANDI= fall panicum, SETLU= yellow foxtail, ECHCG= Barnyardgrass,

Table 8. Conifer seedling injury in the container study at 2 weeks after treatment.¹

Treatment	Rate	BHS	CBS	DF	EWP	WS	CA	FF
Kg ai/ha		Injury Ratings						
		2003	2004					
Terbacil	1.12	2.0	1.0	1.0	1.2	1.0	1.0	1.0
Flumioxazin	0.28	3.0	1.0	1.0	1.0	1.0	1.0	1.0
Mesotrione	0.28	3.0	1.2	1.0	1.0	1.0	1.0	1.0
Imazaquin	0.42	2.0	1.1	1.0	1.1	1.0	1.0	1.0
Trifloxysulfuron	0.01	1.0	1.3	1.0	1.1	1.0	1.0	1.0
Isoxaben+Trifluralin	1.12+0.84	2.0	1.0	1.0	1.0	1.0	1.0	1.0
Imazapic	0.070	3.0	1.2	1.0	1.0	1.0	1.0	1.0
Lactofen	0.28	4.0	1.8	1.0	1.2	1.0	1.0	1.0
Rimsulfuron	0.025	3.0	1.0	1.0	1.0	1.2	1.0	1.0
Untreated	---	1.0	1.0	1.0	1.0	1.0	1.0	1.0
LSD (0.05)		NS	NS	NS	NS	NS	NS	NS

¹ Abbreviation: NS, not significant. If no year is indicated the mean was pooled across 2003 and 2004.

Injury was graded from 1 to 10 scale (1= no injury, 10= dead plant)

Table 9. Conifer seedling injury in the container study at 6 weeks after treatment. ¹

Treatment	Rate	BHS	CBS	DF	EWP	WS	CA	FF
	Kg ai/ha	2003	2003	2003	2004	2003	2004	2004
----- Injury Ratings -----								
Terbacil	1.12	9.6	7.3	2.0	5.0	4.6	2.0	6.5 7.5 8.2
Flumioxazin	0.28	5.5	4.3	2.7	1.2	1.6	1.2	1.2 1.0 1.0
Mesotrione	0.28	7.5	3.0	1.0	2.2	1.6	1.2	3.0 1.7 1.7
Imazaquin	0.42	8.5	4.0	1.0	2.0	3.0	1.0	1.0 1.5 1.7
Trifloxysulfuron	0.01	4.2	4.3	1.0	1.7	1.8	1.0	1.2 1.0 1.2
Isoxaben+Trifluralin	1.12+0.84	7.0	2.5	1.5	2.2	1.5	1.2	1.5 1.0 1.2
Imazapic	0.070	8.2	5.3	1.0	1.0	1.1	1.5	1.0 1.0 1.0
Lactofen	0.28	9.3	4.5	1.5	1.0	3.8	1.5	1.7 1.0 1.0
Rimsulfuron	0.025	7.5	2.0	2.0	1.5	1.2	1.5	1.5 1.0 1.2
Untreated	---	1.0	1.0	1.0	1.0	1.0	1.0	1.0 1.0 1.0
LSD (0.05)		5.0	2.6	NS	1.0	2.0	NS	1.11 1.23 0.69

¹ Abbreviation: NS, not significant. If no year is indicated the mean was pooled across 2003 and 2004.

Injury was graded from 1 to 10 scale (1= no injury, 10= dead plant)

Table 10. Size index difference in the container study for 2004.¹

Treatment	Rate	CBS	DF	WS	FF ²	EWP	CA ²
Kg ai/ha ----- cm -----							
Terbacil	1.12	1.50	4.12	1.88	0.00	3.75	1.00
Flumioxazin	0.28	5.62	6.25	6.25	5.87	4.50	4.12
Mesotrione	0.28	6.63	7.88	6.25	5.50	6.63	3.88
Imazaquin	0.42	3.88	7.63	6.37	4.00	1.25	3.63
Trifloxysulfuron	0.01	6.00	6.88	8.00	5.88	7.75	6.00
Isoxaben+Trifluralin	1.12+0.84	6.75	8.88	5.00	5.75	5.75	5.50
Imazapic	0.070	3.88	7.75	8.12	6.25	7.38	6.63
Lactofen	0.28	7.50	6.50	8.25	5.13	7.00	5.63
Rimsulfuron	0.025	6.13	6.38	7.00	6.38	5.50	6.50
Control	---	7.63	8.88	8.50	4.88	6.00	4.50
LSD (0.05)		NS	NS	NS	2.0	NS	2.2

¹ Abbreviation: NS, not significant. Plant size index difference = plant size index (November) – plant size index (June)

² Size index difference significant (P<0.05)

Table 11. Number of weeds in the container study at 6 weeks after treatment in 2004.

Treatment	Rate	SONOL ¹	AMARE	PANDI	MOLVE	MEDLU
	Kg ai/ha	-----Number of weeds / pot -----				
Terbacil	1.12	0	0	0	0	0
Flumioxazin	0.28	0	0	0	0	0
Mesotrione	0.28	0	0	0.8	0	0
Imazaquin	0.42	0	0	10.8	0	1.8
Trifloxysulfuron	0.01	0	0	1	0	0
Isoxaben+Trifluralin	1.12+0.84	0	0.3	2.5	1	1.5
Imazapic	0.070	0	0	12.3	0.3	2.3
Lactofen	0.28	0	0	1.3	0	0.5
Rimsulfuron	0.025	0	0	0.3	0	0
Untreated	---	6.8	2.5	18.3	11.8	2.5
LSD (0.05)		1.7	1.3	3.3	2.1	1.3

¹ SONOL= annual sowthistle, AMARE= redroot pigweed, PANDI= fall panicum, MOLVE= carpetweed,

MEDLU= black medic

CHAPTER VI: HERBICIDE EFFICACY ON DIFFERENT WEED SPECIES

INTRODUCTION

Nursery and greenhouse production represents the sixth largest agricultural commodity group in the United States. This is the fastest growing segment of the U.S. agriculture; between 1991 and 1998 sales of this segment increased 30%. Nursery growth is caused by the strong U.S. economy with the expansion in housing and increase of ornamental plant consumption (Knox et al. 2003).

Nurseries and floriculture operations in the states of California, Florida, Michigan, Oregon, Pennsylvania, and Texas use 335 active ingredients and a total of 4.77 million pounds of chemicals; herbicides account for 20% (984,000 pounds) of the total amount. Glyphosate is the most popular herbicide, being used in 26% of the operations, followed by oxyfluorfen used in 8%, and oryzalin used in 6% of the operations (Anonymous 2004).

Economic losses in the nursery industry due to weed infestations have been estimated at \$7,000 per acre. Nurseries may spend \$500 to \$4000 per acre of containers for manual removal of weeds (Mathers and Case 2003). However, hand-weeding sometimes is necessary regardless of chemical weed control (Knox et al. 2003).

Although growers try to implement non-chemical weed control practices, chemicals are widely used for weed control in nurseries. Herbicides represent 20% of the total amount of pesticides used in the nursery and floriculture industries in California, Florida, Michigan, Oregon, Pennsylvania, and Texas (Anonymous 2004). A survey in Florida showed that 71% and 56% of nurseries use postemergence and preemergence herbicides, respectively, and almost half used both kinds of herbicides (Tatum and Thompson 1993).

Yellow nutsedge (*Cyperus esculentus* L.) is a perennial weed of most agricultural, horticultural, and nursery crops as well as turfgrass and landscape (Uva et al. 1997). It is listed as one of the most troublesome weeds for the ornamental industry. Yellow nutsedge grows in many soil types and propagates primarily by tubers and rhizomes. These characteristics make this weed very hard to control once established in the field. In addition, there are not many effective herbicides to control yellow nutsedge.

Metolachlor is the only preemergence herbicide currently labeled for nursery crops that is effective against nutsedge (Altland et al. 2003). Metolachlor at 3.3 kg and 6.6 kg ai/ha provided excellent yellow nutsege control at both rates and the combination of metolachlor plus simazine also provided excellent yellow nutsedge and annual grass control at 12 WAT (Setyowati et al. 1995). Metolachlor and other acetanilides herbicides adsorption to the soil is controlled mainly by the content of organic matter in the soil (Weber et al. 2003).

Halosulfuron applied foliarly at 0.009 and 0.018 kg/ha provided 87 to 91% purple nutsedge and 79 to 84% yellow nutsedge control. Re-growth measurements taken 5 WAT showed 88 to 90% and 75 to 83% reduction in purple nutsedge and yellow nutsedge resprouting respectively (Hurt and Vencill 1994a). In addition, yellow nutsedge re-growth for halosulfuron, imazapic, glyphosate, and MSMA was below 5% of the untreated control (Ferrell et al. 2004).

Imazapic and imazaquin control many annual broadleaf weeds as well as the perennial yellow nutsedge. Both have similar symptoms in plants, including growth inhibition, chlorosis of meristematic areas and general chlorosis and necrosis (Vencill 2002). Imazaquin was one of the most effective preemergence treatments for reducing

yellow nutsedge shoot weight (89%). Imazaquin at 0.25 and 0.5 kg ai/ha applied postemergence reduced yellow nutsedge shoot weight by 72 to 77% at 2 WAT, comparable to chlorimuron (83%) , pyridate (82%), bentazon (82%), and glyphosate (87%) (Derr and Wilcut 1993). Hurt et al. (1994b) obtained 70 to 77% of yellow nutsedge control and 56 to 59% of purple nutsedge control with imazaquin applied at 0.43 kg/ha and 0.56 kg/ha, respectively. Foliar application of imazapic at 0.070 kg/ha controlled 95% purple nutsedge and 61% yellow nutsedge (Hurt and Vencill 1994b).

Imazapic applied postemergence at 0.05 and 0.07 kg ai/ha, imazethapyr applied preplant incorporated or postemergence at 0.07 kg ai/ha, and metolachlor applied preplant incorporated at 1.7 kg ai/ha controlled yellow nutsedge at least 75%, but imazapic controlled yellow nutsedge more consistently than the others. Yellow nutsedge tuber densities in herbicide-treated plots were 51 to 75% less than in untreated control plots (Grichar 2002).

Imazaquin and imazethapyr were the most effective preemergence treatments for reducing yellow nutsedge shoot weight. Applied postemergence, they reduced yellow nutsedge shoot weight by 72 to 87% at 2 WAT (Derr and Wilcut 1993).

Bentazon, halosulfuron, and imazaquin are effective postemergence nutsedge herbicides (Altland et al. 2003). Imazaquin, bentazon and glyphosate applied postemergence reduced yellow nutsedge shoot weight by 72 to 87% at 2 WAT (Derr and Wilcut 1993). In addition, regrowth from bentazon was 44% of the control and was the least effective herbicide tested, whereas halosulfuron and imazapic were most effective for yellow nutsedge control (Ferrell et al. 2004).

Yellow nutsedge control with mesotrione was inconsistent. Increasing the rate of mesotrione from 0.070 to 0.140 kg/ha, and adding atrazine, improved control of yellow nutsedge at 56 DAT (Summerlin et al. 2000). Mesotrione was less effective reducing nutsedge regrowth compared to halosulfuron and MSMA. Mesotrione-treated yellow nutsedge regrowth was 58% of the control regrowth, while regrowth from halosulfuron and MSMA treatments was between 0 and 5% (Earl et al. 2004).

Trifloxysulfuron applied to yellow nutsedge or purple nutsedge leaves is absorbed and translocated acropetally and basipetally, and no more than 4% is translocated to tubers and roots. Half-life of trifloxysulfuron on the plant was estimated at 4 h in both purple and yellow nutsedge (Troxler et al. 2003). The effect of trifloxysulfuron plus 0.25% NIS (non-ionic surfactant) was similar when applied at four or six-leaf stages of yellow nutsedge (Singh and Singh 2004). Soil-applied trifloxysulfuron reduced shoot number, shoot weight, and root weight more than foliar-applied trifloxysulfuron (McElroy et al. 2003).

Bispyribac will be used to control grasses, sedges, and broad leaf weeds in rice production. Another potential use is in non-cropland weed control (Vencill 2002).

Flumioxazin gives good preemergence control of many broadleaf weeds. The mode of action is believed to be inhibition of protoporphyrinogen oxidase, an enzyme important in the synthesis of chlorophyll; after absorption, porphyrins accumulate in susceptible plants causing photosensibilization, which leads to membrane peroxidation. Plants emerging from treated soil become necrotic and die shortly after sunlight exposure (Vencill 2002). Flumioxazin affects photosynthesis by reducing foliar chlorophyll and

carotenoid contents, gas exchanges and alteration in plastid structure. As a result, plantlet growth was greatly inhibited (Saladin et al. 2003).

Rimsulfuron controlled yellow nutsedge 40 to 70% and nutsedge control was not increased with the addition of glyphosate in the tank mixture (Nelson and Renner 2002).

Mugwort (*Artemisia vulgaris* L.) is a rhizomatous perennial with erect flowering stems. Reproduction is usually by rhizomes and rarely by seeds. Its persistent rhizomes make mugwort difficult to control in perennial crops (Uva et al. 1997). Little to no long-term control of mugwort is achieved with applications of glufosinate, metsulfuron, triclopyr, or the dimethylamine salt and the isooctyl ester of 2,4-D, even at exceptionally high use rates. Long-term mugwort control may be achieved with relatively low use rates of picloram (0.28 kg/ha) and clopyralid (0.28 kg/ha), but higher rates are needed for glyphosate (8.9 kg/ha) and dicamba (8.9 kg/ha) to obtain same control (Bradley and Hagood 2002a). In addition, sequential herbicide treatment and sequential mowing are strategies that enhance mugwort control (Bradley and Hagood 2002b).

British yellowhead (*Inula britannica* L.) is a perennial plant that reproduces from seed or roots. It is a relatively new weed to Michigan. It was first reported in Michigan in 1990, but has the potential to become a wide spread weed.

Yellow nutsedge, mugwort, and British yellowhead were selected to study their susceptibility to herbicides. Information obtained from this research will be valuable for the ornamental industry to improve control of these weeds.

MATERIALS AND METHODS

Three experiments were conducted to evaluate herbicide efficiency in yellow nutsedge (*Cyperus esculentus* L.), mugwort (*Artemisia vulgaris* L.), and British yellowhead (*Inula britannica*).

Yellow Nutsedge

Two sets of experiments were conducted in the greenhouse at Michigan State University.

Four tubers were planted in each pot filled with high organic media (sphagnum peat 70 – 80%) in August 5, 2004. The tubers were obtained from Azlin Seed Service, Leland MS. Four days after planting, the following preemergence herbicides were applied: flumioxazin (0.28 kg ai/ha), metolachlor plus flumioxazin (2.1 lb ai/a, 0.28 kg ai/ha), and metolachlor (2.1 kg ai/ha) were sprayed. Postemergence herbicides were applied on August 20, 2004 when nutsedge had five to six leaves (15 cm height). Postemergence treatments were bentazon (1.12 kg ai/ha), bispyribac (0.07 kg ai/kg), glyphosate (0.56 and 1.12 kg ai/ha), halosulfuron (0.07 kg ai/a), imazapic (0.07 kg ai/ha), imazaquin (0.56 kg ai/ha), mesotrione (0.1 kg ai/ha), trifloxysulfuron (0.007 kg ai/ha), rimsulfuron (0.025 kg ai/ha), and an untreated control. Soil media was moist at application time.

All treatments were applied with a bench sprayer utilizing a teejet nozzle 8001E, 172 kPa pressure, 187 L/ha output and 1.6 km/h speed.

Yellow nutsedge control was evaluated 2 weeks after postemergence applications. The rating was done visually on a scale of 1 to 10, 1= no control and 10= 100% control.

Plants were counted and cut on September 7, 2004. Plants were dried for four days at 45 C and weighed. The statistical model was a randomized complete block with five replications.

The same procedure was followed in the second experiment except that a different media was used, which was a mixture of 50% sandy loam soil, 30% peat, and 20% sand. In this experiment foliage re-growth was cut and weighed again at 3 weeks after the first cut. The four tubers were planted on August 24, 2004 and the preemergence herbicides were applied on August 26. The postemergence herbicides were applied on September 10, 2004. Weed control evaluation was done on September 23. Nutsedge plants were counted, cut, weighed and dried on September 28.

Hosta infested with British yellowhead

Container experiment

Container and field experiments were conducted at the Horticulture Teaching & Research Center, East Lansing, Michigan.

Hosta spp. and British yellowhead were grown together in 4 L containers. The soil type was loamy sand containing sand 82%, silt 13%, and clay 5%. Pieces of 4 to 5 cm British yellowhead roots were placed in the containers containing hosta plants. Root pieces were taken from British yellowhead plants grown in the greenhouse. At application hostas were 10 to 30 cm high and British yellowhead size varied greatly among containers from 5 to 35 cm. Clopyralid rate is between 0.105 to 0.28 kg ai/ha. In our study three different rates (0.10, 0.14, or 0.21 kg ai/ha) within the recommended range were applied with or without organosilicone surfactant (OSS) (Silwet L-77,

Loveland Industries Inc., Greeley, CO) at 0.5% v/v in July 18, 2003. There was also an untreated control.

Treatments were applied with a backpack CO₂ sprayer and two nozzle boom (FF 9502, Teejet® nozzle, Spraying Systems Co, Wheaton, Illinois) at 172 kPa and 187 L/ha. At application time the air temperature was 24 C, the relative humidity 38%, 15% cloudy, wind speed 8 km/h, and soil in the container was moist.

After spraying, all pots were placed in a lathehouse with 60% shade. Hosta injury and British yellowhead control were visually rated on a 1 to 10 scale, with 1= no injury or no weed control and 10= 100% dead plants or complete weed control. Ratings were done 4 and 9 weeks after herbicide application.

A randomized complete block design with four replications was used for the experiment. The data were analyzed with SAS.

The experiment was repeated in 2004. The procedure was the same, treatments were applied on July 1, and air temperature at application time was 26 C, relative humidity 42%, wind 11 km/h from the west.

Field experiment

A field experiment was conducted to determine Hosta spp. susceptibility to clopyralid in field conditions. Clopyralid was applied at 0.10, 0.14, or 0.21 kg ai/ha with or without OSS at 0.5% v/v. An untreated control was left for comparison. A randomized complete block design with 3 replications was used. Each replication had one row of hostas and treatments were assigned randomly in each replication. Plots were 3 m long and had 6 to 8 plants. Soil was a loamy sand containing sand 83%, silt 9%, and clay 7%

and the pH was 6.0. Treatments were applied on July 18, 2003. The same scale was used for crop injury. Injury was rated at 2, 4, and 9 WAT. At the application time air temperature was 24 C, soil temperature 28 C, relative humidity 39%, and wind speed was 10 km/h from the east.

Mugwort

Two sets of experiments were conducted at the Horticulture Teaching & Research Center.

Three to four pieces of mugwort rhizomes (3 to 5 cm long) were planted in 2 L containers filled with sandy clay soil in June 2003. The rhizomes were taken from original plants grown in the greenhouse. Clopyralid 0.14 or 0.28 kg ai/ha, glufosinate 1.12 kg ai/ha, flumioxazin 0.28 kg ai/ha (plus NIS 0.25 % v/v), bentazon 1.12 kg ai/ha (plus NIS 0.25 % v/v), mesotrione 0.10 kg ai/ha, bentazon plus mesotrione (1.12 and 0.10 kg ai/ha) (plus COC 1.0 % v/v), bispyribac 0.07 kg ai/ha (plus NIS 0.25 % v/v), trifloxysulfuron 0.007 kg ai/ha (plus NIS 0.25 % v/v), and glyphosate 1.12 kg ai/ha were applied on July 7, 2004. One plot was left as a control. Mugwort plants were 5 to 15 cm high at application.

Treatments were applied with a CO₂ backpack sprayer with a two nozzle boom (FF 11002 nozzles) at 172 kPa and 187 L/ha output. At application the air temperature was 20 C, the relative humidity 69%, 100% cloudy, wind speed 3 km/h, and the soil in containers was moist.

After application the plants were placed in a poly house. Treatments were visually rated at 2 and 8 WAT as described above.

The second experiment was conducted similarly as explained above, except that plants were placed in a shady area in a lath house after application. Herbicides were applied on July 14, 2004. Temperature was 21 C, 80% cloudy, relative humidity was 71%.

Randomized complete block with four replications was used for statistical analysis in both trials.

RESULTS AND DISCUSSION

Yellow Nutsedge

Results vary between the two experiments mainly due to the different type of soil utilized in each experiment.

In the high organic soil study (Table 1), non of the treatments provided complete nutsedge control. The best weed control was achieved by halosulfuron (7.4). Mesotrione, glyphosate (1.12 kg ai/ha), imazapic, trifloxysulfuron, imazaquin, rimsulfuron, and bispyribac provided fair control of 5.6 to 6.4. The rest of the treatments provided poor control (rating < 3.8). In addition, the preemergence treatments gave the lowest weed control.

Halosulfuron, imazapic, trifloxysulfuron, and imazaquin reduced nutsedge biomass.

In the second experiment, preemergence herbicides were the most effective in controlling yellow nutsedge (Table 2). The combination of flumioxazin plus metolachlor was the best treatment, with a visual rating of 9.4 at 2 WAT. Metolachlor alone provided good control (7.0) and flumioxazin alone fair control (5.2). Among the postemergence

herbicides, trifloxysulfuron and halosulfuron had the best control, with 5.8 and 5.6, respectively. The other treatments resulted in poor control within a range of 3.0 to 4.8.

Metolachlor plus flumioxazin, metolachlor, trifloxysulfuron, and halosulfuron had the lowest nutsedge dry weight at 2 WAT. In addition, number of plants was significantly different between treatments. Flumioxazin plus metolachlor and metolachlor had the lowest number of plants. The other treatments were not different from the control (Table 2).

Dry weight of nutsedge regrowth at 5 WAT was significantly reduced by all treatments, except for bispyribac, glyphosate (0.56 kg ai/ha), and rimsulfuron, which were not different from the control (Table 2). Imazaquin, imazapic, mesotrione, trifloxysulfuron, and halosulfuron did not provide good control, but regrowth in these treatments was zero at 5 WAT. In addition, the number of live plants per pot was zero in these treatments, except for trifloxysulfuron which was 0.2 (Table 2).

Hurt and Vencill (1994a) obtained 75 to 83% of yellow nutsedge regrowth reduction at 5 WAT in nutsedge treated with halosulfuron at 0.009 and 0.018 kg/ha, respectively. In our study, regrowth was zero at 5 WAT, but the rate used was 0.07 kg ai/ha. In addition, Ferrell (2004) obtained less than 5% regrowth with imazapic and halosulfuron, both applied at 0.07 kg/ha.

High organic matter in the soil reduced the activity of metolachlor, flumioxazin and their combination against yellow nutsedge. As suggested by Weber (2003), metolachlor adsorption in the soil was positively related with the amount of organic matter in the soil. The high amount of organic matter in our research could lead to a high adsorption of metolachlor, thus reducing significantly its activity. In addition,

metolachlor and flumioxazin, especially in combination, provided excellent weed control when applied to nutsedge grown in soil with low organic matter content.

Among postemergence herbicides, halosulfuron, mesotrione, and glyphosate (1.12 kg ai/ha) had the best yellow nutsedge control in organic soil, while trifloxysulfuron and halosulfuron had the best control in mineral soil (Table 1 and 2).

Imazaquin, imazapic, mesotrione, trifloxysulfuron, and halosulfuron had medium nutsedge control at 2 WAT, but they prevented 100% nutsedge regrowth at 5 WAT. Similar results were obtained by Derr et al. (1993). They obtained 95% regrowth reduction at 8 WAT with a lower imazaquin rate (0.5 kg ai/ha). In addition, Grichar et al. (2002) found that imazapic consistently controlled nutsedge and also reduced the number of tubers. Even though imazaquin, imazapic, mesotrione, trifloxysulfuron, and halosulfuron did not have high control ratings at 2 WAT, there is evidence that these may be used in long term nutsedge control programs.

Hosta infested with British yellowhead

Containers

Mean separation was pooled across years because crop injury by year interaction and weed control by year interaction were not significant.

All treatments caused injury to hosta at 4 and 9 WAT (Table 3). Due to the mode of action of clopyralid, which is a growth regulator, injury consisted mainly of distorted growth such as twisted and rolled leaves. Clopyralid at 0.14 kg ai/ha plus OSS and clopyralid at 0.1 kg ai/ha produced the lowest injury at 2 WAT. At 9 WAT all treatments had significant injury within a range of 2.7 to 3.2.

The addition of OSS did not increase or reduce hosta injury at 4 or 9 WAT (Table 3). Clopyralid 0.21 kg ai/ha plus OSS, clopyralid 0.21 kg ai/ha, clopyralid 0.14 kg ai/ha plus OSS, and clopyralid 0.1 kg ai/ha plus OSS resulted in the highest British yellowhead control at 4 and 9 WAT (Table 3). Addition of OSS to the lowest rate increased weed control comparable to the highest rates.

Field

In the field, no treatment caused crop injury at 2 WAT (Table 4). However, clopyralid at 0.1 and 0.14 kg ai/ha without the addition of OSS were the only treatments without injury compared to the control at 4 and 9 WAT. The other treatments produced injuries within a range of 2.3 to 3.3. The addition of OSS caused a slight but not significant increase in injury at all clopyralid rates. This result contrasts with those obtained from the containers in which the addition of OSS did not show any influence on hosta injury rates.

In conclusion, clopyralid injured hosta at all rates tested either in the container and field experiment, except for the field experiments for the lower rates (0.1 and 0.14 kg ai/ha) without OSS. Clopyralid at 0.1 and 0.14 kg ai/ha without OSS, not only had reduced injury in the field but also provided 6.2 and 6.7 British yellowhead control in the container study. Even though not significantly different, the addition of the surfactant tended to increase injury in the field but not in the container study and increased British yellowhead control. OSS increase droplet surface tension in leaves allowing clopyralid to be absorbed more rapidly, thus, causing an increase in British yellowhead control but also an increase in crop injury.

Further studies on a larger scale are needed to obtain information about the effect of OSS and other potential adjuvants in a clopyralid tank mix on British yellowhead control and hosta injury. Since injury consisted in increased leaf twisting, knowing the impact of these injuries on crop marketability will be useful for rate adjustments.

Mugwort

The interaction of weed control by treatment trial was significant at 2 and 8 WAT, so data is presented by trial in Table 5.

First trial

Bentazon plus mesotrione, glufosinate, and glyphosate resulted in the best mugwort control at 2 WAT. However, at 8 WAT, bentazon plus mesotrione and glufosinate control declined to 6.0 and 4.0 respectively, while glyphosate and clopyralid at 0.28 kg ai/ha still had excellent control. The lower rate of clopyralid provided good mugwort control (7.5) at 8 WAT. Flumioxazin provided mugwort control 8.3 and 7.0 at 2 and 8 WAT, respectively. Trifloxysulfuron, bentazon, and mesotrione controlled mugwort 6.3, 3.0, and 2.8 at 8 WAT, respectively. Bispyribac provided very poor control being not different from the untreated control.

Second trial

Flumioxazin and glufosinate had excellent control at 2 WAT, but it declined to 5.8 and 2.8 at 8 WAT. Same results were observed in the first trial (Table 5). Clopyralid at 0.28 kg ai/ha had medium control at 2 WAT but was excellent (9.3) at 8 WAT.

Bentazon plus mesotrione controlled mugwort 6.8 at 2 WAT and 8.8 at 8 WAT. The other treatments provided mugwort control within a range of 3.8 to 4.8.

In conclusion, inconsistent results were observed between trials. However, clopyralid at 0.28 kg ai/ha had the best mugwort control in both trials. This agrees with Bradley et al. (2002), who suggested that low rates of clopyralid (0.28 kg ai/ha) may control mugwort in the long term. Bentazon plus mesotrione and glyphosate had excellent mugwort control in one of the two trials. Bradley et al (2002) reported complete mugwort control after one year of applying a high rate of glyphosate (8.9 kg ai/ha). However, in our study the 1.12 kg ai/ha rate was too low to achieve acceptable control in our second trial. Bentazon plus mesotrione had a complementary effect on mugwort control in both trials. In addition, glufosinate gave excellent early control but control declined 60-70% at 8 WAT. This result agrees with Bradley et al. (2002) who observed 50% control after one year of treatment at a higher rate (8.9 kg ai/ha) of glufosinate.

Research in sequential applications of different herbicides, different modes of action, with different rates and timing is necessary to implement a more efficient mugwort control program.

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Table 1. Yellow nutsedge control, dry weight and number of plants per container at 2 weeks after treatment in greenhouse after treatment with pre and postemergence herbicides; grown in containers with high organic soil.

Herbicide	Rate	Timing	Rating ¹	Dry weight	Live plants
----- 2 WAT -----					
	kg ai/ha			g/pot	number
Flumioxazin	0.28	Pre	1.6	4.82	3.0
Flumioxazin +					
Metolachlor	0.28 + 2.1	Pre	2.2	3.14*	2.6
Metolachlor	2.1	Pre	1.8	3.57*	2.8
Bentazon	1.12	Post	2.4	2.66*	3.4
Bispyribac	0.07	Post	3.8	1.63*	3.0
Glyphosate	0.56	Post	2.0	3.5*	3.0
Glyphosate	1.12	Post	6.4	0.97*	3.2
Halosulfuron	0.07	Post	7.4	0.54*	3.4
Imazapic	0.07	Post	5.8	0.64*	3.0
Imazaquin	0.56	Post	5.6	0.73*	3.2
Mesotrione	0.1	Post	6.4	1.09*	3.0
Rimsulfuron	0.025	Post	5.6	1.07*	3.6
Trifloxysulfuron	0.007	Post	5.8	0.81*	3.0
Untreated	---	---	1.0	4.88	2.8
LSD (0.05)			1.1	0.86	NS

¹ Control rating was taken on a scale of 1 to 10, meaning 1= no weed control, and 10=complete weed control. * Indicates significantly different from the untreated at $P \leq 0.05$.

Table 2. Yellow nutsedge control, dry weight, and number of plants per pot in greenhouse conditions; grown in containers with mineral soil.

Herbicide	Rate	Timing	Rating ¹		Dry Weight	No. of plants	Dry Weight	No. of plants
			2 WAT	2 WAT	2 WAT	5 WAT	5 WAT	
	kg ai/ha			g/pot	number	g/pot	number	
Flumioxazin	0.28	Pre	5.2*	0.79*	3.0	0.14*	1.6*	
Flu+Met	0.28 + 2.1	Pre	9.4*	0.11*	1.8*	0.01*	0.4*	
Metolachlor	2.1	Pre	7.0*	0.29*	1.8*	0.06*	0.6*	
Bentazon	1.12	Post	4.8*	0.75*	2.8	0.15*	1.0*	
Bispyribac	0.07	Post	4.6*	1.02*	3.0	0.55	2.4	
Glyphosate	0.56	Post	3.0*	1.36*	2.6	0.49	2.6	
Glyphosate	1.12	Post	4.8*	1.14*	3.4	0.21*	1.6*	
Halosulfuron	0.07	Post	5.6*	0.69*	3.4	0*	0*	
Imazapic	0.07	Post	3.6*	1.41*	3.6	0*	0*	
Imazaquin	0.56	Post	4.8*	0.75*	3.0	0*	0*	
Mesotrione	0.1	Post	4.4*	0.85*	3.6	0*	0*	
Rimsulfuron	0.025	Post	4.8*	0.76*	2.8	0.66	2.4	
Trifloxysulfuron	0.007	Post	5.8*	0.58*	2.4	0*	0.2*	
Untreated	---	---	1.0	2.21	3.0	0.65	3.0	
LSD (0.05)			1.7	0.58	1.0	0.21	0.8	

¹ Control rating was taken on a scale of 1 to 10, meaning 1= no weed control, and 10=complete weed control. * Indicates significantly different from the untreated at $P \leq 0.05$.

Table 3. Hosta injury and Inula control in the container study at 4 and 9 weeks after application of clopyralid.¹

Treatments	Rate	Timing	Hosta injury ²		Inula control ³	
			4 WAT	9 WAT	4 WAT	9 WAT
Clopyralid	0.1	Post	2.6	2.7	4.4	6.2
Clopyralid + OSS ²	0.1	Post	2.7	2.9	5.9	7.6
Clopyralid	0.14	Post	2.8	3.2	5.1	6.7
Clopyralid + OSS	0.14	Post	2.7	3.0	6.1	8.1
Clopyralid	0.21	Post	3.0	3.0	6.6	8.6
Clopyralid + OSS	0.21	Post	3.4	3.2	7.6	9.0
Untreated	---		1.0	1.0	1.0	1.0
LSD (0.05)			0.6	0.8	1.6	2.2

¹ 2003 and 2004 data was combined for analysis.

² OSS= Silwet L-77 added at 0.5% v/v

³ Ratings: 1= no weed control or no crop injury, and 10=complete weed control or dead plant.

Table 4. Hosta injury in the field study at 2, 4 and 9 weeks after application of clopyralid in 2003.

Treatments	Rate	2 WAT	4 WAT	9 WAT
	Kg ai/ha	----- rating ^y -----		
Clopyralid	0.1	1.7	1.7	2.0
Clopyralid + OSS ²	0.1	2.0	2.7*	2.7*
Clopyralid	0.14	1.7	1.3	1.7
Clopyralid + OSS	0.14	2.3	2.7*	2.3*
Clopyralid	0.21	2.0	2.3*	3.3*
Clopyralid + OSS ¹	0.21	1.7	2.7*	3.0*
Untreated	---	1.0	1.0	1.0
LSD (0.05)		NS	1.2	1.0

² OSS= Silwet L-77, added at 0.5% v/v

^y Injury rating 1= no injury, and 10= dead plant

* Indicates significantly different from the untreated at $P \leq 0.05$.

Table 5. Mugwort control at 2 and 8 WAT in both trials conducted in 2004.

Treatment	Rate	First trial ¹		Second trial ¹	
		2 WAT	8 WAT	2 WAT	8 WAT
	kg ai/ha	-----rating ^x -----			
Bentazon + NIS	1.12	4.0	3.0	4.5	4.0
Bentazon +					
mesotrione + COC ^y	1.12 + 0.1	9.0	6.0	6.8	8.8
Bispyribac + NIS	0.07	2.0	2.3	2.5	3.8
Clopyralid	0.14	5.0	7.5	2.0	4.0
Clopyralid	0.28	6.3	8.8	6.0	9.3
Flumioxazin + NIS ^y	0.28	8.3	7.0	8.8	5.8
Glufosinate	1.12	10	4.0	10	2.8
Glyphosate	1.12	9.3	10	2.8	4.5
Mesotrione	0.1	2.5	2.8	4.0	4.8
Trifloxysulfuron + NIS	0.007	2.8	6.3	4.8	4.0
Untreated	---	1.0	1.0	1.0	1.0
LSD (0.05)		1.2	1.6	1.4	2.6

¹ Herbicides were applied on July 7, 2004 for the first trial and July 14, 2004 for the second trial.

^y Crop oil concentrate (COC) applied at 1% v/v and non ionic surfactant (NIS) at 0.25 % v/v.

^x Weed control rating 1= no control, and 10= 100% control.

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