

INTEGRATED MANAGEMENT OF THE INVASIVE WEED, CUT-LEAVED
TEASEL (*Dipsacus laciniatus* L.) ALONG A MISSOURI HIGHWAYS

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TEASEL (*Dipsacus laciniatus* L) ALONG A MISSOURI HIGHWAYS

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ABSTRACT

Cut-leaved teasel is an invasive, exotic, and noxious weed in Missouri. It infests areas along highways and minimal disturbance sites. Cut-leaved teasel outcompetes native species and also reduces traffic visibility. Field studies regarding seed biology, detection with digital images, and implementation of an implementation of an integrated management program (herbicides and seeding desirables grasses). Seed characteristics such as viability after flowering, seedling emergence patterns and persistence under field conditions were evaluated under field conditions in central Missouri. Hyperspectral images were collected along interstate highway I-70 during mid-july, when cut-leaved teasel was flowering. Twenty targets were selected with unsupervised classification. Hyperspectral (63bands) and multispectral (12 bands) images were processed for supervised classification using maximum likelihood and spectral angle mapper supervised classification after 20 targets were selected with unsupervised classification. For managing areas where teasel was detected, chemical control with triclopyr, aminopyralid, dicamba and metsulfuron-methyl was applied and grasses sown (tall fescue, Canada wildrye and buffalograss) .

Cut-leaved teasel produced viable seed that germinated 12 days after flowering. Seed emerged primarily in April and October, with total emergence up to 31% of seed established. Most of the seed (from 75 to 81%) was lost or died after three years under field conditions; only 6.1% remained viable. Cut-leaved teasel was detected using

maximum likelihood classification with 80% accuracy using hyperspectral images. Maximum likelihood classification produced higher accuracy classification compared to spectral angle mapper classifier. Application of aminopyralid herbicide in November and May, along sowing tall fescue, Canada wildrye and buffalograss, were the best combination to reduce infestations of cut-leaved teasel. While herbicide programs involving dicamba and metsulfuron-methyl resulted in acceptable control of cut-leaved teasel, control with triclopyr was poor (25% control one year after treatments). The development of biology information regarding cut-leaved teasel demonstrated that management under field conditions will require several years. The combination of remote sensing and management with herbicides/grasses can be effective on roadside habitats. The integration of biology, detection, and control techniques lead to the optimum suitable cut-leaved management plan.

CHAPTER I

Introduction

RESEARCH JUSTIFICATION

Teasels (*Dipsacus* spp.; *Dipsacales*: Dipsacaceae) are categorized as exotic and invasive weeds in non-agricultural habitats (Sforza 2004). Originally from Eastern Europe and Western Russia, teasel was introduced in the western USA for the textile industry to divide wool strands (tease or card) prior to spinning (Ryder 1996). Demand for teasel was minimal with few hectares used in production. Later abandoned as mechanical devices replaced teasel, plants spread. Solecki (1993) speculated teasel spread rapidly after the construction of the interstate highway system, which could have acted as a dispersal corridor. Teasel spread may also have been facilitated from the use of seedheads in floral arrangements (Rector et al. 2006).

Dipsacus laciniatus, *D. fullonum*, and *D. silvestris* are the most representative species of teasel present in the U.S., with a distribution in more than 40 states. Common teasel, also known as *Dipsacus fullonum* L., was the cultivated teasel (Ferguson and Brizickly 1965), with *Dipsacus sylvestris* Huds. recognized as the wild teasel (Mullins 1951, Ryder 1996; Werner 1975c). Botanically, *Dipsacus fullonum* has a sharply hooked scale between the florets instead of very small spines as found in *D. sylvestris*. This was a special characteristic desired by the textile industry to separate wool strands (Mullins 1951). *Dipsacus sylvestris* is considered a subspecies of *D. fullonum* (Ferguson 1965, USDA 2006). Similarly, *Dipsacus sativus* is recognized as Indian teasel (USDA 2008) or Fullers' teasel (Ryder 1996), and is identified as a subspecies of *D. fullonum* (Ferguson

and Brizicky 1965; Ryder 1996). Cut-leaved teasel (*Dipsacus laciniatus* L.) has deeply serrated or lacinate leaves, white flowers and short involucre bracts (Solecki 1993). In addition to these features, cut-leaved teasel is generally a larger more robust plant (Solecki 1993).

Cut-leaved teasel (*Dipsacus laciniatus* L.) is the species that has aggressively colonized roadside habitats and unmanaged or low maintenance areas such as pastures, railroad right-of-ways, cemeteries, forest edges, natural parks and conservation areas. There are no known natural enemies (insect, disease, and animal) of cut-leaved teasel in infested areas, which limits development of biocontrol agents; consequently, teasel is free to proliferate (Glass 1991; INHS 1990). Today, teasel is present in 43 states, being absent in southeastern states, North Dakota, Alaska, and Hawaii (USDA 2008). While *D. fullonum* has spread throughout 40 states, cut-leaved teasel mainly occurs in 19 states in the northern part of the US. Cut-leaved teasel has been declared noxious in Colorado, Iowa, Oregon, and Missouri (Rector et al. 2006; USDA 2008)

There are three major problems associated with the presence of cut-leaved teasel in different environments. First, cut-leaved teasel reduces native species in conservation areas and natural parks and consequently, modifies nutrient and hydrologic cycles (Huenneke and Thomson 1994; Solecki 1993; Werner 1977). Second, taproot plants such as cut-leaved teasel change the soil moisture levels by reducing infiltration in comparison to species with fibrous root systems (grasses); this increases runoff (Lacey et al. 1989). Finally, according to the Missouri Department of Transportation (MoDOT), flowering

teasel plants can reach up to 2.1 meters tall, reducing visibility of traffic signs and increasing the hazards to motorists (Rand Swanigan, personal communication¹)

BIOLOGY

Teasel is a biennial plant that emerges from seed in the spring and fall. Seedlings form a flat rosette during the first year, followed by a flowering stalk during the second summer. After seed maturation is complete, plants die to allow establishment of new seedlings (Caswell and Werner 1978; Jurica 1921). Reproduction is only by seed, with 87.5 % allogamy or cross-pollination of plants (Werner 1975c).

The majority of cut-leaved teasel seed is dispersed within 1.5 m of the parent plant (Werner 1975a), because seeds lack adaptations for wind or animal distribution (Werner 1972). The seed dispersal pattern results in dense patches or communities of teasel plants. Mowing equipment, flooding and careless disposal of flower arrangements have facilitated the dispersion of teasel (Czarapata 2005). Neubert and Caswell (2000) documented that teasel spread move from Ontario, Canada to the east coast of North America (650 km) in 13 years. They speculated that teasel had some mechanism that facilitated the transport of seed, as the rate of spread averaged 27 km/year. Water transport can be one of these mechanisms, because teasel seed can float up to 22 days in water with no reduction in viability (Werner 1975c). In addition, mowing along roadsides serves as a seed dispersal mechanism. Solecki (1993) observed that teasel populations along a highway spread rapidly where mowing was a common practice.

¹ Rand Swanigan Head of Roadside Management and Maintenance for MoDOT.

Cut-leaved teasel seed dispersal following the maturation of plants is facilitated by the loose association of seeds in open ventricles in the capitulum. Seed germination occurs in both fall and spring (Caswell and Werner 1978; Werner 1975c). No stratification or period of light exposure is required for teasel germination. In a laboratory trial, teasel germination was greater than 95% (Werner 1975a, 1975d); however, germination decreased to 28 to 86% under different field conditions in Michigan (Werner 1975c).

Establishment of teasel in a new site depends upon successful seed germination and seedling survival. Cut-leaved teasel requires “open spots” for germination and successful establishment; seedlings are sensitive to competition (Werner 1975d, 1977). Seed that do not germinate remain viable for only 2 years in Michigan, (Werner 1977a) and up to 5 years in Warwick, UK (Roberts 1986).

Morphological features such as a strong rosette, deep taproot and hard spines confer a competitive advantage for teasel compared to other species. Established rosettes cover the ground with layers of wide leaves. This reduces the space and light available for other species (Huenneke and Thomson 1994; Rector et al. 2006). The total leaf area index (LAI) value for cut-leaved teasel in Missouri was estimated to be around 3 (Bentivegna 2006), suggesting that plants intercepted 95% of the available light (Blackman and Black 1959). In addition, taproots can reach up to 5 cm in diameter and 45 to 75 cm long (Werner 1975c). This large taproot allows plants to extract moisture and nutrients from a deeper soil profile than grasses. Taproots reduce water infiltration compared to a grass root system, thereby increasing runoff (Lacey et al. 1989). The taproot is a storage site for photosynthates, enabling rapid re-growth of plants in early

spring or after occasional mowing. Finally, spines on the stems and leaves, together with large receptacular bracts beneath flowers dissuade grazing by herbivores.

Leaves of teasel are large, entire or undulate, lanceolate to oblanceolate, with spines on the lower midrib. Leaves of the flowering stalk are prickly, opposite, basally connate, and forming a cup which often holds water (Jurica 1921; Maguirre 1959). Cut-leaved teasel exhibits a deep serration or lacinate leaves (hence the species name) (Solecki 1993). Bentivegna (2006) reported that the total leaf area per cut-leaved teasel plant is equivalent in both the vegetative and reproductive stage; however, plants have fewer and larger leaves in the vegetative compare to reproductive stage.

Some research suggests that teasel does not enter the reproductive stage until rosettes reach a minimum of 30 cm in diameter (Werner 1975b). This suggests that plants have stored sufficient resources in the taproot for flowering. Although most of the plants reach the minimum rosette size in the second year, some rosettes under stress conditions (interspecific competition) (Werner 1972) or high plant density (intraspecific competition) (Harper and White 1974) may not reach the critical rosette size and remain in the vegetative stage for several growing seasons (Werner 1975b). In a field dominated by herbaceous perennials, *D. sylvestris* rosettes did not produce flowers until four years following establishment in Michigan (Werner 1975b).

After the vegetative period is complete, teasel plants produce a stem up to 2.5 m in length, which branches and has opposite leaves (Bentivegna 2006, Werner and Caswell 1977b). A terminal seedhead or capitulum (2 to 10 cm large) is borne at the end of each stem (Szabó 1923, Werner 1975b), with flowers densely arranged. The fruit is an achene, 4 to 5 mm in length (Solecki 1993). The number of seedheads varies with intraspecific

competition. In Missouri, the number of cut-leaved teasel capitulum varied from six to thirty-six per plant, with and without intraspecific competition, respectively (Bentivegna and Smeda 2007). Werner (1975b) observed one to thirty-five capitulum for *D. sativus* plants in Michigan. The size of the plant affects the number of inflorescence per plant, with three to nine capitulum commonly reported. In fact, plants that are taller and more vigorous are likely to have larger seedheads (Hedberg and Hedberg 1977). Seedheads are subtended by involucre bracts, which are an effective deterrent to herbivore feeding (Solecki 1993). The primary or central seedhead is the largest one, usually flowers first, and can produce from 656 to 1,487 seeds (Bentivegna 2006).

Cut-leaved teasel plants produced up to 12,600 seeds without intraspecific competition, while plants growing in dense monospecific communities produced only 4,300 seeds (Bentivegna and Smeda 2007). A single cut-leaved teasel plant in Illinois produced up to 3,000 seeds, with 30 to 80% of the seeds viable (Glass 1991). Similarly, plants of *D. sylvestris* in Michigan produced up to 3,300 seeds (Werner 1975c). Seed maturation time may be short because plants that were cut during or shortly after flowering were able to produce viable seeds (Solecki 1989).

MANAGEMENT

Cut-leaved teasel management strategies must focus on decreasing the density of plants, preventing seed production, and limiting seed dispersal. Management of cut-leaved teasel includes treatment of rosettes with herbicides and mowing flowering plants.

Teasel management techniques include mechanical and chemical programs. Mechanical control includes hand roguing, cutting, and sparse burning. Chemical control involves the application of postemergence selective herbicides (Glass 1991; Solecki 1993).

Hand roguing is effective for small or isolated patches. However, this is time-consuming and expensive (Solecki 1989). Mowing is the most common practice for teasel management along roadsides. However, “Mowing does not eradicate your vegetation problem, it delays or hides them” according to the Illinois Department of Transportation (Caylor 1998). There are two major problems associated with mowing teasel plants. First, plants are cut prior to flowering new shoots emerge and produce viable seed (Glass 1991). Second, when plants were cut during flowering, seeds matured rapidly, resulting in viable seed (Cheesman 1998). In the United Kingdom, Cheesman(1998) showed changes in seed production depended upon the time of mowing.

In non-cropped areas where a significant amount of thatch exists, the burning of dead plant residues eradicate teasel. However, succulent rosettes in spring cover areas infested with teasel and impede the spread of fire. Although rosettes suffered fire damage, many recovered and later produced seed (Solecki 1993). Burning teasel may only work in conjunction with other management techniques (Solecki 1993).

The most effective practice for teasel control is application of postemergence herbicides (Caylor 1998; Missouri Vegetation Management Manual 1997). Currently, there are only six herbicides labeled for teasel control: sulfometuron-methyl, metsulfuron-methyl, chlorsulfuron, triclopyr + clopyralid, aminopyralid, and dicamba (Crop Protection Reference 2006). Others herbicides including 2,4-D, glyphosate, and

imazapyr have shown promise for control of teasel (Bentivegna 2006; Glass 1991; Missouri Vegetation Management manual 1997). The combination of 2,4-D with triclopyr, picloram, and clopyralid resulted in 85% control of cut-leaved teasel (Bentivegna 2006).

Some herbicide treatments were made when other desirable vegetation was dormant or absent (late in the fall or early in the spring), which resulted in effective control of teasel with minimal damage to desirable species (Missouri Vegetation Management Manual 1997; Solecki 1993). Application of herbicides to teasel lacking photosynthetically active tissue has resulted in inconsistent results (Missouri Vegetation Management Manual 1997).

REMOTE SENSING APPROACH

Invasive plants have principal characteristics that allow them to multiply very quickly. They thrive in a wide variety of environmental conditions, are not a host for disease, insects or other organisms, and reproduce rapidly (Czarapata 2005). Land managers for areas infested with invasive weeds must achieve a suitable level of control of weeds while minimizing inputs. Plants forming small infestations pose few obstacles for control. However, larger infestations require systematic evaluation and implementation of control measures to be successful. Remote sensing technologies are an important tool to enhance weed management and improve or protect the environment (Shaw 2005a).

Remote sensing consists of the acquisition and recording of information about an object (e.g. plant, soil, or water) without touching it. That information passes to a sensor through reflectance and data recorded as a digital image. Digital images are a regular grid array in which a digital number (DN) represents the brightness of one object in each cell (pixel). In each pixel, reflectance for a specific wavelength of light or band yields a special composition of the present object in that area. Several specific wavelengths or bands can compose one image (Gibson and Power 2000).

The unique reflectance of one object at a specific time of the year defines the term spectral signature. Plants, water, or bare soils are differentiated from each other through variations in spectral signatures. For instance, plants can easily be distinguished from other targets in the near infrared spectrum (700-900nm), because larger differences are found there than in the visible range of the spectrum (Gibson and Power 2000; Hutto et al. 2006; Peña-Barragán et al. 2006).

Spectral signatures of a plant species vary with their phenological stage. Principally, leaves (number, orientation, chemistry and structure), mineral nutrition, and water content are parameters that affect the spectral signature (Gibson and Power 2000). Sometimes it is hard to identify a unique spectral signature for one species because of variations in fertility, water content, and rapid phenological changes. Plants of different species can have spectral similarities, while plants of the same species can have high variability depending upon phenological stage (Brown and Noble 2005). However, under similar phenological stages and environmental conditions, it is possible to distinguish accurately different species under field conditions using remote sensing. For example, Koger et al. (2004b) under field conditions discriminated pitted morningglory (*Ipomoea*

lacunosa) at different growth stages from soybeans (*Glycine max*) in at variable densities with an accuracy of 93 to 99 % (Koger et al. 2004b).

With identification of the spectral signature of one target, it is possible to assign one pixel to a land class according to particular spectral reflectance. The classification of pixels provides a map distribution of one special target. In fact, land classification and direct mapping of individuals or associations, together with changes in vegetation detection, are the most used features of remote sensing. There are two ways to assign a pixel to a land class: supervised and unsupervised classification. In supervised classification, pixels are classified according to known targets (spectral signature reference). Conversely, unsupervised classification occurs when the pixels are grouped according to the statistical structure and do not require specific information about the features included in the image (Campbell 2002).

Even though remote sensing technologies are very useful tools for determination, evaluation, and evolution of weed infestation; there are special issues related to the spatial, temporal, spectral, and radiometric resolution that can impact success. Spatial resolution (the size of the pixel), spectral resolution (the ability of a sensor to define fine wavelength interval), radiometric resolution (ability of sensor to discriminate slight differences of energy), and temporal resolution (how often data are taken) are four important features which distinguish changes in land cover composition (Nagendra 2001). Weed size, infestation level, and frequency of evaluation are the most important characteristics to determine the sensor and platform. For example, sensors carried by aircraft and satellite are able to detect specific weeds at a spatial resolution of 0.5 to 4 m and 3 to 40 m, respectively (Shaw 2005b).

Working with resolution limitations on digital images, remote sensing has been used successfully for detecting weed infestations in variable environments such as rangeland (Everitt et al 2001; Lass et al 2005), turgrass (Hutto et al. 2006), prairie (Casady et al. 2005), water (Everitt et al. 1999; Marshall and Lee 1994), and conservation areas (Zhou 2006). Much of the weed detection work has occurred in agriculture crops, where there exists a homogeneous canopy. Applications include: sugarbeet and maize (Vrindts et al. 2002); wheat (López-Granados et al. 2006); soybean (Koger et al. 2004a, 2004b; Medlin et al. 2000); mint (Gumz and Weller 2006); and carrot (Merges et al. 1985). To date, there is little documented use of remote sensing in roadside environments. This environment is highly variable, with many different species intermixed.

Remote sensing is useful in detecting invasive plants (Underwood et al. 2003). However, there are two keys for weed management impacting the use of remote sensing: phenological plant stage during the year and detection when plant densities are low. Weed identification involves determining the unique time during the plants growth stage when phenological differences between species are greatest (Everitt and Deloach 1990; Shaw 2005b; Underwood et al. 2003). Early detection of invasive weeds is essential for minimizing the size of patches in infested areas and detecting weeds that have spread to new areas. Control is cost-efficient for small patches compared to larger infestations.

An effective weed management program economically reduces teasel patches along roadsides without reducing the diversity of native plants. The concept of site-specific management (SSM) describes the analysis of temporal and spatial data of one area to allow targeting infested areas. Site-specific weed management (SSWM) involves

implementation of management techniques at a site when weed infestations can cause economical losses (Shaw 2005b). There are several benefits to using SSWM, such as reduced costs, increased efficacy, and reduced overall contamination. For example, applying a specific herbicide only in localized patches versus broadcast applications reduces the cost of herbicide treatment as well as increases the efficacy of the specific compound (Shaw 2005b). Shaw (2005b) estimated that herbicide inputs declined 60% when an herbicide was applied in locations only where weeds were found. In other words, specific herbicides are more effective when applied to a specific weed spectrum at each location (Shaw 2005b).

JUSTIFICATION

Introduction of invasive weeds occurred initially for food, ornamental, and fiber production practices, with plants later spreading to new areas. Pimentel et al. (2005) estimated the spread of invasive weeds at approximately 700,000 ha/year in wildlife habitats in the US. There are approximately 5,000 introduced plants in the US that have escaped control. Alien plants reduce crop production by about \$24 billion, and over \$3 billion annually are spent on herbicides used to control alien plants (Pimentel et al. 2005). Five billion dollars is the estimated amount spent to control invasive, alien plants in pastures and rangelands (Pimentel et al. 2001).

The management cost for non-indigenous, invasive weeds totals \$137 billion each year (Pimentel et al. 2000); the same author assigned a cost of \$120 billion per year, five years later (Pimentel et al. 2005). The cost for management of invasive weeds is

increasing. However, beyond the actual cost, it is difficult to calculate the value of a desirable species that becomes extinct, the loss of biodiversity, ecosystem services, and increases in erosion. The annual cost of managing invasive plants is greater than all natural disasters combined (NASA 2008). Due to the amount of money involved in invasive weed control, the mapping and measurement of invasive plant distributions as well as an understanding of the affects of invasion on native species is critical to improving management of invasive weeds.

A number of biology studies related to the growth and development of teasel plants are available (Bentivegna 2006; Solecky 1989, 1993; Werner 1975b, 1975c.). However, vital information such as the maturation period for seeds, flowering, characterization of seedling emergence, and seed persistence is not currently available.

Among management techniques, the screening of commonly used broadleaf herbicides can identify effective compounds in a roadside environment. Teasel seedlings or other species of invasive weeds can occupy areas of bare soil created by senescing teasel plants. The removal of existing plants should accompany the filling of open spaces with desirable grasses. Maintaining an environment with a dense stand of grasses should minimize the establishment of teasel, and reduce additional management techniques necessary to exclude teasel.

Aerial digital images are easily acquired for habitats with limited access; this facilitates a non-destructive method for mapping weed infestations. A ground-based survey of weed species along highway I-70 is very difficult to accomplish, because of the continuous traffic (40,000 vehicles per day; Rand Swanigan personal communication¹).

Generation of a teasel infestation map should allow site-specific management including herbicide application and the establishment of desirable grasses.

Development of a methodology for isolation of a unique spectral signature for teasel could lead to determining signatures for other invasive weeds. The creation of the spectral signature library allows identification of weeds at different growth stages, searching for small infestations, and isolation of weeds in areas with mixed populations. The generation of a specific weed map may not only assist in determining the level of infestation of each weed, but also in the distribution of that species along a roadside. The success of herbicide programs for control of teasel and assessment for the introduction of grasses can be monitored with aerial digital images. Additionally, aerial images can determine changes in weed populations for untreated areas, allowing determination of how quickly invasive weeds are spreading. Relevant biology studies together with the use of remote sensing allow the implementation of rational management programs for cut-leaved teasel.

LITERATURE CITED

- Bentivegna, D.J. 2006. Biology and management of cut-leaved teasel (*Dipsacus laciniatus* L.) in central Missouri. M.S. Thesis University of Missouri. 67 p.
- Bentivegna, D.J. and R.J. Smeda. 2007. Biology and management of cut-leaved teasel (*Dipsacus laciniatus* L.) in Missouri. Proceedings of Weed Science Society of America 47:230.
- Blackman, G.E. and J.N. Black. 1959. Physiological and ecological studies in the analysis of plant environment. XII. The role of the light factor in limiting growth. Annals of Botany 23:131-145.
- Brown, R.B. and S.D. Noble. 2005. Site-specific weed management: sensing requirements- what do we need to see?. Weed Science. 53:252-258.
- Campbell, J.B. 2002 Introduction to remote sensing. 3rd ed. New York:Guilford Press. 622 p.
- Caswell, H. and P. A. Werner. 1978. Transient behavior and life history analysis of teasel (*Dipsacus sylvestris* Huds.). Ecology 59(1):53-66.
- Casady, G.M., R.S. Hanley, and S.K. Seelan. 2005 Detection of leaf spurge (*Euphorbia esula*) using multirate high-resolution satellite imagery. Weed Technology. 19:462-467.
- Caylor, P. 1998. Herbicides help Illinois DOT control roadside weeds. American City and Country 113:17-18.

- Cheesman, O.D. 1998. The impact of some field boundary management practices on the development of *Dipsacus Fullonum* L. flowering stems, and implication for conservation. *Agriculture, Ecosystems and Environment* 68: 41-49.
- Crop Protection Reference. 2006. C & O press. 302 5th Avenue New York, NY 10117-1058. 2395 p.
- Czarapata, E.J. 2005. Invasive plant of the upper midwest. An illustrate guide to their identification and control. The University Wisconsin press. Madison, WI. 215 p.
- Everitt, J.H. and C.J. Deloach. 1990. Remote sensing of Chinese tamarisk (*Tamarix chinensis*) and associated vegetation. *Weed Science*. 38:273-278.
- Everitt, J.H., D.E. Escobar, and M.R. Davis. 2001. Reflectance and image characteristic of selected noxious rangeland species. *Journal of Range Management*. 54:A106-A120.
- Everitt, J.H., C Yang, D.E. Escobar, C.F. Webster, R.I. Lonard, and M.R. Davis. 1999. Using remote sensing and spatial information technologies to detect and map two aquatic macrophytes. *Journal of Aquatic Plant Management*. 37:71-80.
- Ferguson, I.K. 1965. The genera of Valerianaceae and Dipsacaceae in the southeastern United States. *Journal of Arnold Arboretum* 46:218-231.
- Ferguson, I.K and G.K.Brizicky. 1965. Nomenclatural notes on *Dipsacus fullonum* and *Dispacus sativus*. *Journal of the Arnold Arboretum* 46:362-365.
- Gibson, P.J. and C.H. Power. 2000. Introductory remote sensing digital image processing and applications. ed. Routledge press, New York, N. 244 p.

- Glass, W.D. 1991. Vegetation management guideline: cut-leaved teasel (*Dipsacus laciniatus* L.) and common teasel (*Dipsacus sylvestris* Huds.). *Natural Areas Journal* 11:213-214.
- Gumz, M.S. and S.C. Weller. 2006. Using spectral vegetation indices for weed detection in mint. *Proc. North Central Weed Sci. Soc. Milwaukee, WI.* 60.
- Harper, J.L. and J. White. 1974. The demography of plants. *Annual Review of Ecology and Systematics.* 5:419-463.
- Hedberg, I. and O. Hedberg. 1977. The genus *Dipsacus* in tropical Africa. *Botaniska notiser* 129: 383-389.
- Huenneke, L. F. and J.K. Thomson. 1994. Potential interference between a threatened endemic thistle and an invasive nonnative plant. *Conservation Biology* 9:416-425.
- Hutto, K.C., D.R. Shaw, J.D. Byrd Jr., and R.L. King. 2006. Differentiation of turfgrass and common weed species using hyperspectral radiometry. *Weed Sci.* 54:335-339.
- INHS. Illinois Natural History Survey. 1990. Vegetation management guidelines. Cut-leaved teasel (*Dipsacus laciniatus* L.) and Common teasel (*Dipsacus sylvestris* Huds.). *in: Vegetation management manual* ed. Illinois Nature Preserve Commission. 1: 24.
- Jurica, H.S. 1921. Development of head and flower of *Dipsacus sylvestris*. *Botanical Gazette* 71:138-145.
- Koger, C.H., D.R. Shaw, K.N. Reddy, and L.M. Bruce. 2004a. Detection of pitted morningglory (*Ipomoea lacunosa*) by hyperspectral remote sensing. I. Effects of tillage and cover crop residue. *Weed Science* 52:222-229.

- Koger, C.H., D.R. Shaw, K.N. Reddy, and L.M. Bruce. 2004b. Detection of pitted morningglory (*Ipomoea lacunosa*) with hyperspectral remote sensing. II. Effects of vegetation ground cover and reflectance properties. *Weed Science*. 52:230-235.
- Lacey, J. R., C.B. Marlow, and J.R. Lane. 1989. Influence of spotted knapweed (*Centaurea maculosa*) on surface runoff and sediment yield. *Weed Technology*. 3:627-631.
- Lass, L.W., T.S. Prather, N.F. Glenn, K.T. Weber, J.T. Mundt, and J. Pettingill. 2005. A review of remote sensing of invasive weeds and example of the early detection of spotted knapweed (*Centaurea maculosa*) and babysbreath (*Gypsophila paniculata*) with a hyperspectral sensor. *Weed Science* 53:242-251.
- López-Granados, F., M. Jurado-Expósito, J.M. Peña-Barragán, and L. García-Torres. 2006. Using remote sensing for identification of late-season grass weed patches in wheat. *Weed Science* 54:346-353.
- Maguire, B.Jr. 1959. Aquatic biotas of teasel waters. *Ecology* 40:506.
- Marshall, T.R. and P.F. Lee. 1994. Mapping aquatic macrophytes through digital image analysis of aerial photographs: and assessment. *Journal of Aquatic Plant Management* 32:61-66.
- Medlin, C.R., D.R. Shaw, P.D. Gerard, and F.E. LaMastus. 2000. Using remote sensing to detect weed infestations in *Glycine max*. *Weed Science* 48:393-398.
- Merges, R.M., P.R. Nixon, and A.J. Richardson. 1985. Light reflectance and remote sensing of weed in agronomic and horticultural crop. *Weed Science* 33:569-581.
- Missouri Vegetation Management Manual. 1997. ed. Tim E. Smith. Missouri Department of Conservation. P.O. Box 180. Jefferson City. MO. 65102. Pp 44-49.

- Mullins, D. 1951. Teasel growing- An ancient practice. *World Crops*. April. Pp 146-147.
- Nagendra, H. 2001 Using remote sensing to assess biodiversity. *International Journal of Remote Sensing* 22:2377-2400.
- NASA. 2006. Science Serving Society: Invasive Species. LG-2006-1-100-GSFC. Pp 2. http://eosps0.gsfc.nasa.gov/ftp_docs/invasive_species_litho.pdf.
- Neubert, M.G. and H. Caswell. 2000. Demography and dispersal: calculation and sensitivity analysis of invasion speed for structured population. *Ecology* 81:1613-1628.
- Peña-Barragán, J.M., F. López-Granados, M.Jurado-Expósito, and L. García-Torres. 2006. Spectral discrimination of *Ridolfia segetum* and sunflower as affected by phenological stage. *Weed Research* 46:10-21.
- Pimentel, D., R. Zuniga, and D. Morrison. 2005. Update on the environmental and economic cost associated with alien-invasive species in the United States. *Ecological Economics* 52:273-288.
- Pimentel, D., S. McNair, J. Janecka, J. Wightman, C. Simmonds, C. O'Connell, E. Wong, L. Russel, J. Zern, T. Aquino, and T. Tsomondo. 2001. Economic and environment threats of alien plant, animal, and microbe invasions. *Agriculture, Ecosystems and Environment* 84:1-20.
- Pimentel, D., L. Iach, R. Zuniga, and D. Morrison. 2000. Environmental and Economic cost of nonindigenous species in the United States. *Bioscience* 50:53-65.
- Rector, B.G., V. Harizanova, R. Sforza, T. Widmer, and R.N. Wiedenmann. 2006. Prospects for biological control of teasels, *Dipsacus* spp., a new target in the United States. *Biological Control* 36:1-14.

- Robert, H.A. 1986. Seed persistence in soil and seasonal emergence in plant species from different habitats. *Journal of Applied Ecology* 23:639-656.
- Ryder, M.L. 1996. Is the Fuller's teasel (*Dipsacus sativus*) really a distinct species?. *The Linnean: newleter and proceedings of the Linnean Society of London*. 11:21-27.
- Sforza, R. 2004. Candidates for biological control of teasel, *Dipsacus* spp. In: Cullen, J.M., Briese, D.T., Kriticos, D.J., Lonsdale, W.M., Morin, L., Scott, J.K. (Eds.), *Proceedings of the XI International Symposium of Biological Control of Weeds*. CSIRO Entomology, Canberra. Pp. 155-161.
- Shaw, D.R. 2005a. Translation of remote sensing data into weed management decisions. *Weed Science* 53:264-273.
- Shaw, D.R. 2005b. Remote sensing and site specific weed management. *Frontier in Ecology and the Environment* 3:526-532.
- Solecki, M.K. 1989. The viability of cut-leaved teasel (*Dipsacus laciniatus* L.) seed harvested from flowering stems: management implications. *Natural Areas Journal* 9:102-105.
- Solecki, M.K. 1993. Cut-leaved and common teasel (*Dipsacus laciniatus* L and *D. sylvestris* Huds.): profile of two invasive aliens. *in* McKnight, B.N. ed, *Biological Pollution: The control and impact of invasive exotic species*. Indiana Academic of Science, Indianapolis, IN. Pp 85-92.
- Szabó, Z. 1923. The development of the flower of the dipsacaceae. *Annals of Botany* 37: 325-337.
- Underwood, E., S. Ustin, D. DiPietro. 2003. Mapping nonnative plants using hyperspectral imagery. *Remote Sensing of Environment* 86:150-161.

- USDA. 2008. The PLANTS Database, Version 3.5 (<http://plants.usda.gov>). [National Plant Data Center](#), Baton Rouge, LA 70874-4490 USA. Access May 5, 2008.
- Werner, P.A. 1972. Effect of the invasion of *Dipsacus sylvestris* on plant communities in early old field succession. PhD. Thesis Michigan state University. University Microfilms, Ann Arbor, Michigan.140p.
- Werner, P.A. 1975a. A seed trap for determining patterns of seed deposition in terrestrial plant. Canadian Journal of Botany 53:810-813.
- Werner, P.A. 1975b. Predictions of fate from rosette size in teasel (*Dipsacus fullonum* L.). Oecologia 20:197-201.
- Werner, P.A. 1975c. The biology of Canadian weeds 12. *Dipsacus sylvestris* Huds. Canadian Journal Plant Science 55:783-794.
- Werner, P.A. 1975d. The effects of plant litter on germination in teasel, *Dipsacus sylvestris* Huds. The American Midland Naturalist 94:470-476.
- Werner, P.A. 1977. Colonization success of a “Biennial” plant species: experimental field studies of species cohabitation and replacement. Ecology 58:840-849.
- Vrindts, E., J. De Baerdemaeker, and H. Ramon. 2002. Weed detection using canopy reflection. Precision Agriculture 3:63-80.
- Zhou, Bo. 2006. Application of hyperspectral remote sensing in detecting and mapping sericia lespedeza in Missouri. M.S. Thesis University of Missouri. Columbia. MO. 81 p.

CHAPTER II

Cut-leaved Teasel (*Dipsacus laciniatus* L.) Seed Development and Persistence

Abstract: Cut-leaved teasel is an exotic, invasive weed that invades roadsides and other minimally disturbed areas. Few studies have focused on seed characteristics and how that contributes to the spread of plants. Field studies were conducted to determine the viability and germinability of seed after flowering, seedling emergence patterns, as well as seed persistence. Flowering (80% flowers opens) was observed under natural conditions July 24 and 16 for 2004 and 2005, respectively. Harvested seed attained a viability of 43% and germination of 2.5% within twelve days of flowering. Seed weight and viability was optimal 30 days after flowering, yet germination was <32%. Seedling emergence was monitored over a 12 month period with the highest emergence concentrated in April and October; total germination of seed reached 31%. Seed persistence was evaluated over a three year period under field conditions. Up to 84% of seed germinated was in the first year, with 6% of seed remaining viable after three years. Although seed viability was relatively short, the rapid development of seed following flowering and seed emergence in both fall and spring suggest management practices are necessary throughout the year to restrict the spread of cut-leaved teasel.

Nomenclature: teasel, *Dipsacus laciniatus* L, invasive, roadside, DIWLA¹.

Additional Index Words: capitulum, emergence.

¹ Code for *Dipsacus Laciniatus* L. in WSSA-approved *Composite List of Weeds*. Revised 2008. WSSA 810 East 10th street, Lawrence, KS 66044-8897.

INTRODUCTION

Cut-leaved teasel (*Dipsacus laciniatus* L.) is a non-native, invasive weed introduced into the New England states from France in the 18th century for separating wool strands in the textile industry (Terres and Ratcliffe 1979). Following mechanization, teasel was abandoned as a crop and spread principally in roadside habitats and physically undisturbed environments such as railroad right-of-ways, cemeteries, natural parks, and conservation areas (Solecki 1993). In this environment, teasel excludes native species and infested areas with open areas during periods of higher precipitation. This increases soil erosion compared to native grasses.

Plant population dispersal in the US has followed the medians of interstate highways. Solecki (1993) stated that construction of the highway system facilitated the spread of teasel. Currently, cut-leaved teasel is present in 17 states, especially in the northern part of the US (USDA 2008). Furthermore, four states have categorized cut-leaved teasel as a noxious weed: Colorado, Iowa, Oregon, and Missouri. There are three species of *Dipsacus* present in the US: *Dipsacus fullonum* (Fuller's teasel), *D. laciniatus* and *D. sativus* (Indian teasel) (Ferguson 1965). Cut-leaved teasel is distinguished from the others by white flowers, deeply lobed or lacinate leaves, and short involucral flower bracts (Solecki 1993).

The invasiveness of cut-leaved teasel is facilitated by the lack of natural enemies, adaptiveness to a wide variety of habitats, competitiveness with native species, and prolific seed production. Rector et al. (2006) reported possible biological control candidates, most of which are not available in the US. Lacking natural enemies, the deep

root system allows teasel to thrive in low fertility soils, thereby out-competing native species (Werner 1975). Bentivegna (2006) reported that both a high growth rate and leaf area index are the most important features describing the competitiveness of cut-leaved teasel. In addition, individual cut-leaved teasel plants produce from 3 to 56 seedheads and a total of 1,300 to 33,500 seeds (achenes), depending up on intraspecific competition (Bentivegna 2006).

Cut-leaved teasel is a biennial plant that grows as a rosette the first year. Rosettes can reach 117 cm in diameter and have a compact arrangement of leaves that result in three times more leaf area than the equivalent ground area (Bentivegna 2006). This high leaf area dramatically limits available light, resulting in monoculture patches. In the second year, plants produce a 2 m stem and inflorescence. Teasel is primarily a cross-pollinated species, with an estimated 4% self-fertilization (Werner 1975).

Management of cut-leaved teasel involves hand removal, herbicides, and mowing. In small areas, the removal of plants can be accomplished by digging (Glass 1991; Solecki 1993), but this is not practical on larger areas. Postemergence herbicides can be effective on established populations, but information is limited regarding the optimal time of application (Solecki 1993). Mowing is considered by some as a method of teasel management, but by others as a method to spread populations. Caylor (1998) reported that mowing teasel did not reduce infestations, but only delayed seed production. The time of mowing is critical for impacting seed production. When mowing early in the summer, plants were able to re-grow and produce seed. On the other hand, mowing reduced seed production when plants were mowed at the onset of flowering (Cheesman 1998). Mowing in the fall disperses mature seed.

Development of timely control strategies for cut-leaved teasel involves a better understanding of seed development following flowering, emergence, and seed persistence in the soil. Because reproduction is only by seed, the optimal time to apply herbicides or mow plants requires knowledge of important seed parameters. The objectives of this research in central Missouri were to determine the viability of seed after flowering, the pattern of seedling emergence, and the persistence of cut-leaved teasel seed.

MATERIALS AND METHODS

Germination and viability of seeds after flowering

For plants established under natural conditions, principal seedheads with 60% of the flowers open were tagged on July 24, 2004 and July 16, 2005 at two locations near Columbia, MO. Sites included the Bradford Research and Extension Center (hereafter Bradford) and north of Columbia along Highway 63 (hereafter Highway 63). The Bradford site was an abandoned pasture with a mixture of tall fescue (*Festuca arundinacea* Schreb.) and weedy species. The Bradford soil was a Mexico silt loam (fine, montmorillonitic, mesic Udollic Ochraqualfs) with 2.9% organic matter and a pH of 5.9 (NRCS 2008). The Highway 63 site also contained tall fescue. The Highway 63 soil was a Keswick silt loam (fine, smectitic, mesic Aquertic Chromic Hapludalfs) with 2.1% organic matter and a pH of 7.5 (NRCS 2008).

After flowering was complete, each primary seedhead was covered with a semi-transparent paper bag (Lawson 217)² (5 by 25 by 18 cm) to prevent seed from shattering. Eight primary seedheads (first flower seedhead to open and in center of plant) were

² Lawson Bags, 480 Central Ave. , P.O. Box 577, Northfield, IL 60093, USA

collected every 6 days following tagging over a period of three months at each location. Air temperature was registered at the time of flowering through final seed harvest (Figure 2.1). For each seedhead harvested, thirty seeds were removed at random, weighed and stored under two different conditions: room temperature (18 to 22 C) and at 4 C. After 7 months of storage, seeds were placed in Fisher Petri dishes³ (60 by 15mm) inside a growth chamber at high relative humidity ($\geq 75\%$) and alternating temperatures [15 C (8 hours) and 21 C (16 hours)]. Seeds were considered germinated when the radicle reached 0.5 mm in length. For seeds that did not germinate at each location and storage condition, a viability test was conducted by placement in a tetrazolium salt solution of 0.2% w/v for two hours at 33 C (Copeland 1976). Seeds were examined and considered live if the embryo turned red. Evaluation of seeds after flowering involved computing means for the harvest conducted each month. For example, the first 5 harvests were used to obtain the mean of the first month and so forth. For appropriate analysis, data were transformed by arcsine of the square root (Snedecor and Cochran 1956).

Seed emergence

Experiments were established at Bradford on September 11, 2003, and at Bradford and the Horticulture and Agroforestry Center (hereafter New Franklin) near New Franklin, MO on September 15, 2004. Six, 1.5 m² areas were flagged at the beginning of each experiment and maintained for one year. In each plot, 1,500 seeds were planted at a depth of 1 cm and emergence of cut-leaved teasel was recorded monthly by counting individual seedlings. Seedlings were considered emerged when cotyledons were fully expanded. After counting, seedlings were removed from the plot with a broadcast

³ Fisher Scientific. 200 Park Lane Dr.. Pittsburgh, PA. 15275-9943.

application of paraquat at 1.17 kg ai. ha⁻¹ plus 0.0125 v/v non-ionic surfactant. Temperature data were recorded with a StowAway[®] TidbiT[®] temperature logger⁴ at a depth of 2 cm. Data of soil temperature are shown in Figure 2.2. New Franklin was represented by Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs) soil type with a pH of 5.4 and 2.6% organic matter (NRCS 2008). Precipitation was measured from the weather station located at each location (Figure 2.3).

Seed persistence

One hundred fifty seeds, with a mean of 99.5% viability, were placed in polypropylene pots under field conditions at two locations (Bradford and New Franklin) on November 10, 2004. Seeds were placed on polyethylene mesh and covered with 1 cm soil. In the middle of spring, summer and fall, five pots at each location were harvested randomly. Seeds were washed and stored at 4 C. Seed viability was estimated using tetrazolium as described above. During the course of the study, emergence of teasel was monitored. Final data for seed were divided into three categories: germinated, viable and lost/dead.

Data from the three studies evaluated were subjected to analysis of variance using SAS statistical software (SAS 2003). The test of normality for Shapiro Wilk and analysis of residuals for equal variance were determined using PROC UNIVARIATE of SAS with a probability of $p \leq 0.05$ (SAS 2003). Means were separated using Fisher's Protected LSD at $p \leq 0.05$ (Steel and Torrie 1980).

⁴ Onset Computer Corporation. 470 MacArthur Blvd.,Boure, MA 02532. PO Box 3450, Pocasset, MA 02559-3450.

RESULTS AND DISCUSSION

Germination and viability after flowering

Cut-leaved teasel flowering was observed under field conditions on July 24, 2004 and July 16, 2005. More than 90% of seedhead flowering occurred in the first 45 days after initial flowering of the primary seedhead; very few seedheads flowered after 45 days. Selected primary seedheads completed flowering in 4 days after initial flowering. Seed weight and viability as well as germination of teasel increased as seed matured (Table 2.1). Seed weight increased over 300% from 6 to 24 days after flowering. Seed weight reached a maximum at 24 days after flowering in 2005 and 30 days in 2004 (Figure 2.4) In both years, germinable seed were detected at 12 days after flowering (Table 2.1).

Seed viability quickly increased up to 71 % in 2004 and 90% in 2005, 18 days after flowering (Table 2.1). Most of the seed reached greater than 75% viability by 30 days after flowering (Figure 2.5). Storage conditions following seed harvest did not influence the seed viability (Figure 2.5). Seed stored in cool conditions in 2004 reached 100% viability by 42 days after flowering (Figure 2.5). After the initial flowering period (30 days), there were minor changes in the weight or the viability of the seed (Figure 2.4 and 2.5).

Seed germination was monitored for up to 90 day after flowering (Figure 2.6). Germination of seed stored at room temperature was higher compared with storage at cool temperature, which suggests that cut-leaved teasel did not require a stratification

period. While maximum germination occurred for Bradford seed that was stored under room temperature two months after flowering in 2004 (24.3%), maximum germination was 20% for the same location and storage conditions at three months after flowering in 2005 (Figure 2.6). In 2005 versus 2004, air temperatures during flowering were greater (Figure 2.1). This temperature difference was highest at flowering time, which could delay seed maturation, and likely delayed the germination of teasel (Figure 2.6B). In 2004, seed germination increased during the three months after flowering for seed stored at room conditions compared with cold conditions at Bradford, but not for Highway 63 seed (Figure 2.6A). In contrast, seed germination was higher for seed stored at room conditions compared with cold conditions in 2005 (Figure 2.6B).

Viable cut-leaved teasel seed were detected in as few as 12 days after flowering, and increased rapidly for seed harvested up to 30 days after flowering. This is important as it relates to the use of mowing following the onset of teasel flowering. Mowing cut-leaved teasel must be done before mature seeds are produced. Solecki (1989) also reported that viable seeds were produced from teasel seedheads that were cut before flowering was complete. The rapid production of viable seeds for cut-leaved teasel suggests removal of cut stems after mowing to prevent dispersal of viable seed.

Emergence patterns

Cut-leaved teasel emergence was concentrated during two periods of the year (Figure 2.7A,B). Emergence in April and October accounted for 33% of all spread seed. Maximum emergence of cut-leaved teasel was 21% in October of 2004 (Figure 2.6B). After one year of monitoring emergence, cumulative emergence was less than 0.1% of

the potential emergence. Soil temperature (Figure 2.2) during October and April ranged from 5 to 20 and 4 to 20 C, respectively. The lack of emergence in November to March and July to September suggests cut-leaved teasel has a defined temperature range for germination. Precipitation close to 70 mm (Figure 2.3) is also another environment condition that cut-leaved teasel may required to emerge.

Similar to this study, Robert (1986) in the UK reported two periods of emergence for *D. sylvestris* in April (48%) and September (17%). The latitude for that location was 3° 14' 45'' north compared to Columbia, MO. Werner (1975) showed that *D. sylvestris* had high emergence rates in April and September in Michigan. According to Hubbell and Werner (1977), most of *D. sylvestris* emergence occurs late in the spring following seed production, and a small percentage remains dormant. In addition, (Caswell and Werner 1978) showed that only a few seeds emerge in the second year, indicating *D. sylvestris* seeds lack a dormancy mechanism, which could lead to multiple emergence over several years.

Seed Persistence

The dynamics of cut-leaved teasel in the seed bank is shown in Figure 2.8. There was no interaction between location and harvest time; therefore, data were pooled over locations. Seedling emergence was greatest in the first year (2005) (13.3%). with no difference throughout the duration of the study. Maximum seed germination reached 15.9 % (Figure 2.8). Seed viability decreased in the first year from 98 to 20%. However, there was no change in seed viability after the first year (Figure 2.8). After three years, only 6.1% of seed remained viable. The death or loss of teasel accounted for much of the fate

of seed, with 75% after 1 year. There was no significant change in the death/loss of seed after the first year.

Even though seed emergence was greatest in the first year following release, other authors reported 4.8 and 2.2% of seed emergence of *D. sylvestris* in the third and fourth years after sowing, respectively. Robert (1986) concluded that *D. sylvestris* was relatively persistent in April at Warwick, UK. Conversely, Werner (1977) reported that teasel seed two years after sowing were considered dead under natural environmental conditions in Michigan. For example, seed that was dispersed in a thick grass environment was lost. For another invasive weed, musk thistle (*Carduus nutans*) only 1.8% of seed remained viable in the soil 5 years after establishment. (Robert and Chancellor 1979).

The dynamics of teasel seed viability after flowering, emergence patterns and seed persistence indicate that management practices for infested areas must be continuous. Seed emergence in the fall and spring signal that a herbicide program must contain residual materials to prevent seedling establishment. Cut-leaved teasel has two peaks of seed emergence throughout the year, necessitating multiple applications of control measures. Herbicide applications at the beginning of May (spring) and November (fall) are the optimal time to preclude establishment of populations. Because teasel actively grows late into the fall, application of non-selective herbicides at that time may result in reduced damage to dormant grasses (Missouri Vegetation Management Manual 1997).

With viable seed produced just 12 days after flowering, mowing must be initiated before flower initiation to preclude seed production. If the plant is cut after the flowering

period, teasel plants have the ability to complete the maturation of the seed in the cut stem (Solecki 1993). Mowing plants 24 days after flowering can be successful, provided stems are removed from the area.

Finally, seed remains viable for at least three years. For established areas of teasel, monitoring for re-establishment must occur for at least this period of time. It is unclear when seed viability is zero, and this likely depends upon environmental parameters. Cut-leaved teasel plant can produce up to 33,500 seeds when growing in the absence of close competition (Bentivegna 2006). Reaching a maximum emergence of 15.9 %, only one plant per m² is capable of producing more than 5,000 seedlings. This ensures a sufficient amount to sustain monoculture populations; mowing can spread seeds to adjacent areas.

In conclusion, effective control methods for cut-leaved teasel are necessary for a minimum of 3 years following seed production. While herbicide applications should be made in May and November after the peak of cut-leaved teasel emergence, mowing should be conducted before flowering. The key for management is decreasing the amount of seeds available in the seed bank together with the reduction of cut-leaved teasel seedlings and rosettes.

LITERATURE CITED

- Bentivegna, D.J. 2006. Biology and management of cut-leaved teasel (*Dipsacus laciniatus* L.) in central Missouri. M.S. thesis. University of Missouri. 67 p.
- Caswell, H. and P.A. Werner. 1978. Transient behavior and life history analysis of teasel (*Dipsacus sylvestris* Huds.). *Ecology* 59:53-66.
- Caylor, P. 1998. Herbicides help Illinois DOT control roadside weeds. *American City and Country* 113:17-18.
- Cheesman, O.D. 1998. The impact of some field boundary management practices on the development of *Dipsacus fullonum* L. flowering stems, and implication for conservation. *Agriculture, Ecosystems and Environment* 68: 41-49.
- Copeland, L.O. 1976. Seed Viability and Viability Testing. Burgess publishing company eds. *in: Principles of Seed Science and Technology*. Pp 103– 120.
- Ferguson, I.K. 1965. The genera of Valerianaceae and Dipsacaceae in the southeastern United States. *Journal of Arnold Arboretum* 46:218-231.
- Hubbell, S.P. and P.A. Werner. 1979. On measuring the intrinsic rate of increase of populations with heterogeneous life histories. *The American Naturalist* 113 :277-293.
- Glass, W.D. 1991. Vegetation management guideline: cut-leaved teasel (*Dipsacus lacinatus* L.) and common teasel (*Dipsacus sylvestris* Huds.). *Natural Areas Journal* 11:213-214.
- Missouri Vegetation Management Manual. 1997. Tim E. Smith ed. Missouri Department of Conservation. P.O. Box 180. Jefferson City. MO. 65102. Pp 44-49.

- NRCS, 2008. Natural Resources Conservation Service. United States Department of Agriculture. Official Soil Series Descriptions. (<http://soils.usda.gov/technical/classification/osd/index.html>) [Accessed 15 February 2008]. USDA-NRCS. Lincoln, NE.
- Rector, B.G., V. Harizanova, R. Sforza, T. Widmer, and R.N. Wiedenmann. 2006. Prospects for biological control of teasels, *Dipsacus* spp., a new target in the United States. *Biological Control* 36:1-14.
- Robert, H.A. 1986. Seed persistence in soil and seasonal emergence in plant species from different habitats. *Journal of Applied Ecology* 23:639-656.
- Robert, H.H. and R.J. Chancellor. 1979. Periodicity of seedling emergence and achene survival in some species of *Carduus*, *Cirsium* and *Onopordum*. *Journal of Applied Ecology* 16:641-647.
- SAS. 2003. Statistical Analysis System. SAS/STAT User's Guide. Release 9.1. Software version 8e. Cary, NC:Statistical Analysis Systems Institute.
- Snedecor, G.W. and W.G. Cochran. 1956. Statistical methods applied to experiments in agriculture and biology. The Iowa State College Press, Ames, Iowa. 534 p.
- Steel, R.G.D. and J.H. Torrie. 1980. Principles and Procedures of statistics: A Biometrical Approach. McGraw-Hill College press, NY. 633 p.
- Solecki, M.K. 1993. Cut-leaved and common teasel (*Dipsacus laciniatus* L and *D. sylvestris* Huds.): profile of two invasive aliens. McKnight, B.N. eds. *in: Biological Pollution: The control and impact of invasive exotic species*. Indiana Academic of Science, Indianapolis, IN. Pp 85-92.
- Terres, J.K. and B. Ratcliffe. 1979. Teasel, as in tease. *Audubon* 9:108-109.

USDA. 2008. The PLANTS Database (<http://plants.usda.gov>). National Data Center, Baton Rouge, LA 70874-4490 USA. Access May 5, 2008.

Werner, P.A. 1975. The Biology of Canadian Weeds. 12. *Dipsacus sylvestris* Huds. Canadian Journal of Plant Science 55:783-794.

Werner, P.A. 1977. Colonization success of a “Biennial” plant species: Experimental field studies of species cohabitation and replacement. Ecology 58:840-849.

Table 2.1. Mean seed weight, viability, and germination of cut-leaved teasel (*Dipsacus laciniatus* L.) from two locations in central Missouri stored under room temperature and cold conditions following harvest at Bradford and Highway 63 in 2004 and 2005.

Year	Date	Days after flowering	Storage conditions	Bradford			Highway		
				Weight ^a g.	Viability %	Germination %	Weight ^a g.	Viability %	Germination %
2004	07/30	6	Room	1.12 d ^b	0 d	0 b ^b	1.17 d ^b	0 d	0 c ^b
	08/05	12		1.88 c	44.8 c	2.5 b	1.70 c	27.9 c	1.7 bc
	08/11	18		2.34 b	70.7 b	26.7 a	2.49 b	71 b	3.4 b
	08/17	24		3.16 a	88.6 a	14.2 a	3.04 a	85.5 a	12.9 a
	07/30	6	Cold	1.15 d	0 c	0 b	1.20 d	0 c	0 b
	08/05	12		2.23 c	0 c	0 b	2.01 c	0.42 c	0 b
	08/11	18		2.78 b	67.5 b	18.6 a	3.03 b	71.7 b	19.2 a
	08/17	24		3.67 a	94.9 a	22.9 a	3.61 a	94.4 a	15.4 a
2005	07/22	6	Room	1.59 d	0 d	0 b	1.67 d	0 c	0 c
	07/28	12		2.29 c	11.9 c	2.1 b	2.05 c	11.5 b	1.7 bc
	08/03	18		3.04 b	90 b	0.4 b	2.85 b	80.4 a	2.1 b
	08/09	24		3.36 a	93.1 a	30.8 a	3.23 a	77.9 a	17.1 a
	07/22	6	Cold	1.57 d	0 d	0 b	1.71 c	0 c	0 a
	07/28	12		2.82 c	33.6 c	0.4 b	2.35 b	0 c	0 a
	08/03	18		3.57 b	82.7 b	1.3 a	3.13 a	76.8 b	0.4 a
	08/09	24		3.99 a	86.7 a	0.4 b	3.50 a	80.1 a	0.4 a

^a Weight of 100 seeds

^b Means inside each location, year and storage condition with the same letter were not different according to Fisher's Protected LSD at $p \leq 0.05$.

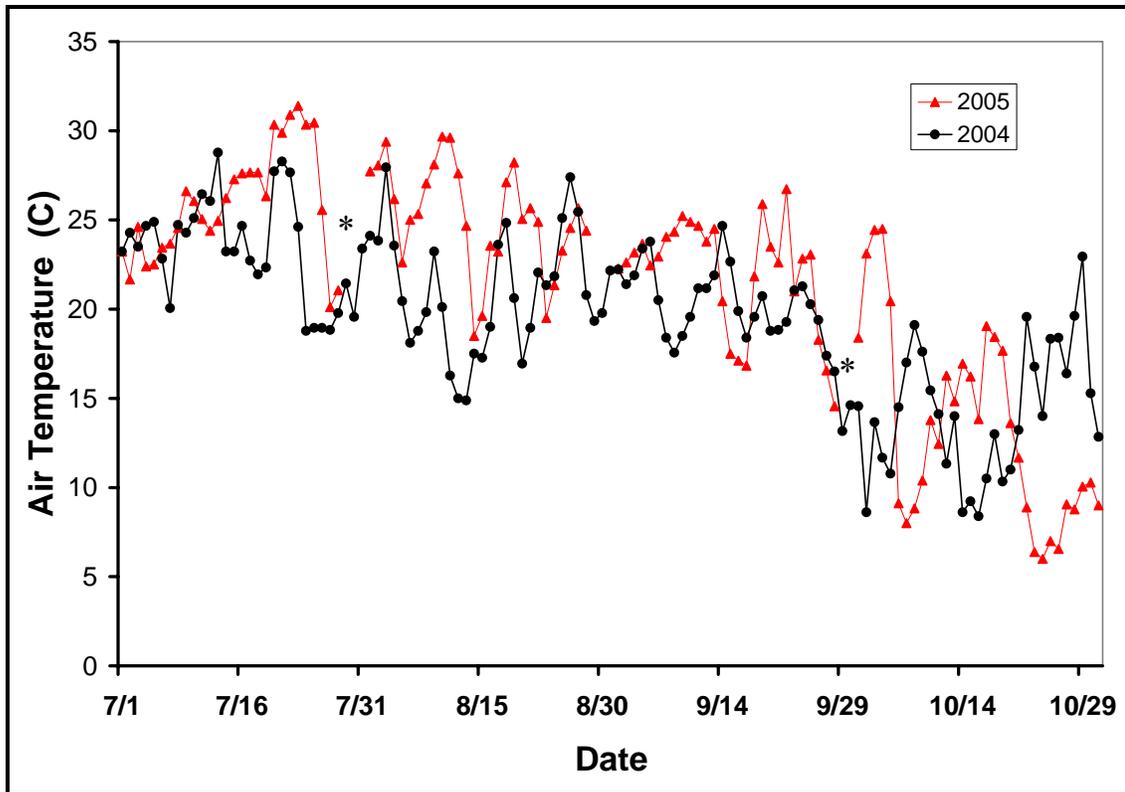


Figure 2.1. Daily mean air temperature during cut-leaved teasel flowering and seed maturation in 2004 and 2005 for central Missouri. Source: Bradford Research and Extension Center. * data not recorded.

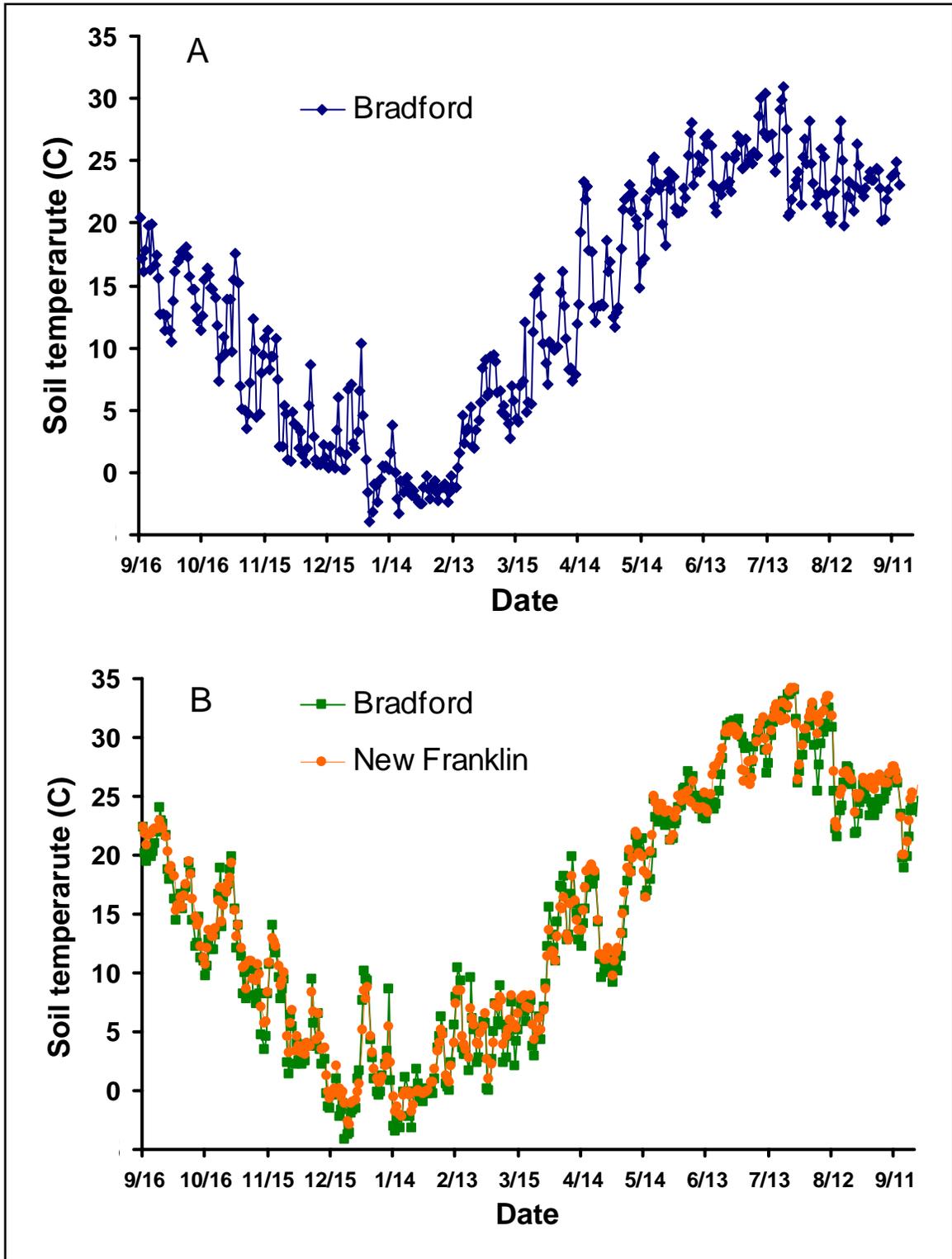


Figure 2.2. Means soil temperature measured in the first 2 cm of the surface in A) (2003/2004) and B) (2004/2005) in Bradford and New Franklin.

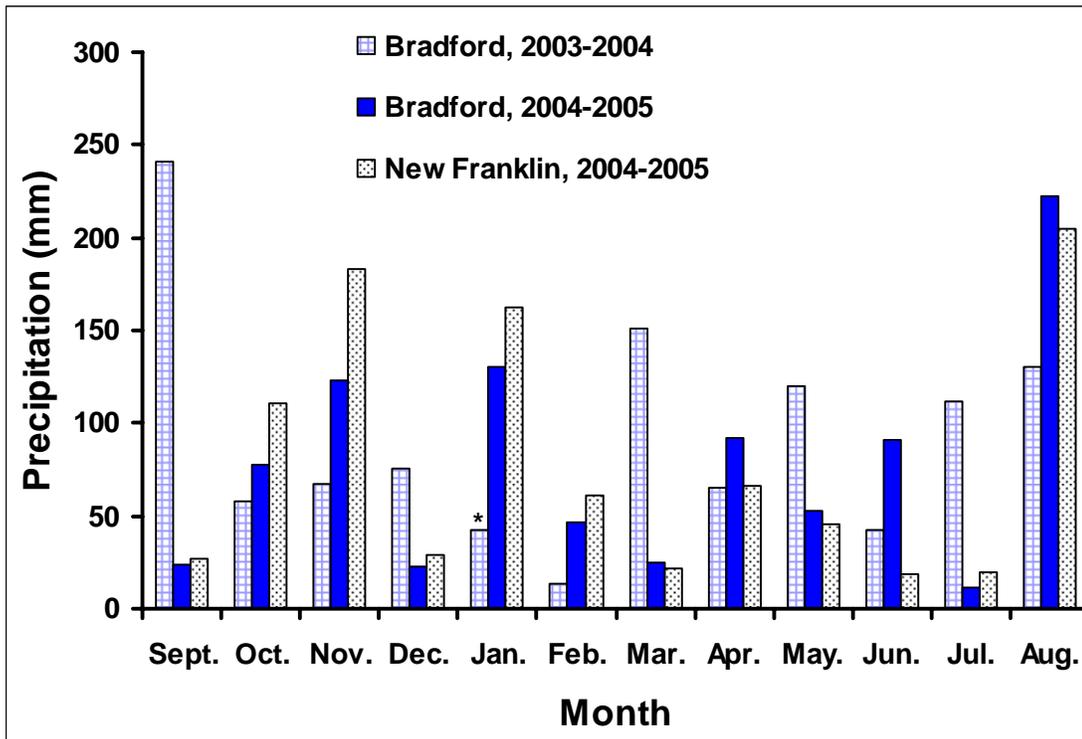


Figure 2.3. Total monthly precipitation at Bradford (2003/2004; 2004/2005) and New Franklin (2004/2005). Source: New Franklin Research Horticulture and Agroforestry Research Center (HARC), Howard County and Bradford Research and Extension Center, Boone County, MO. * 20 days data no recorded.

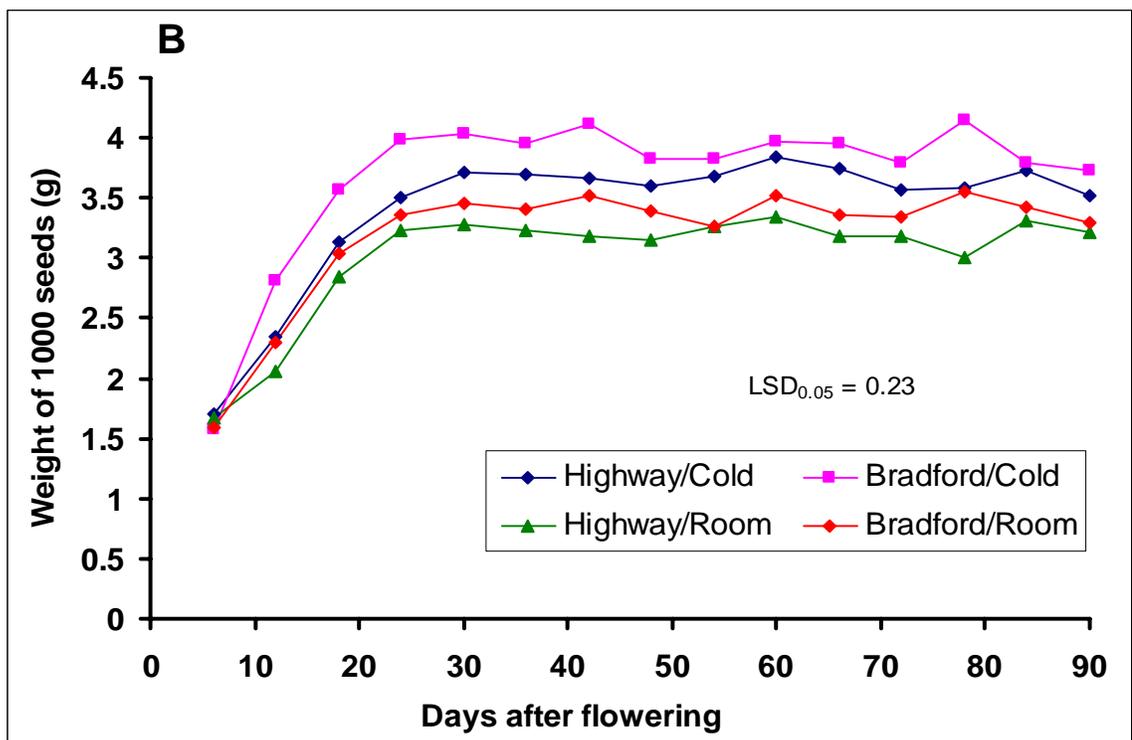
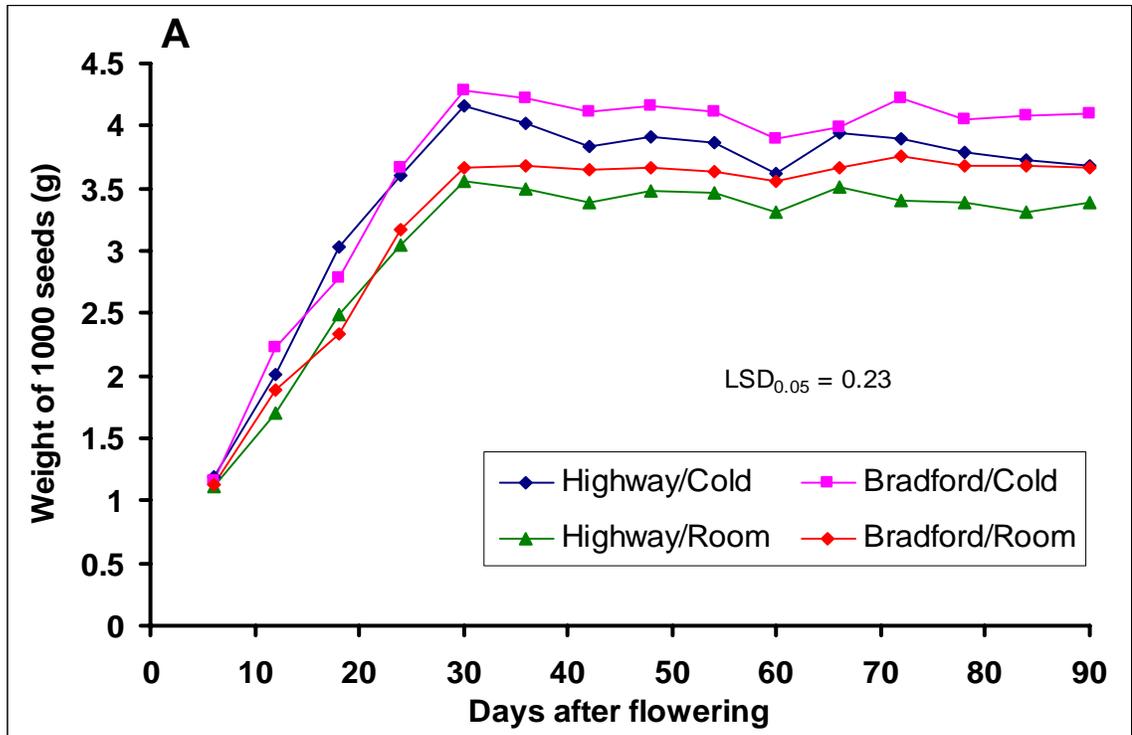


Figure 2.4. Cut-leaved teasel (*Dipsacus laciniatus* L.) seed weight at different periods after flowering. Seed stored at room and cold conditions from samples harvested in 2004 (A) and 2005 (B) for two locations in central Missouri (Bradford and Highway 63).

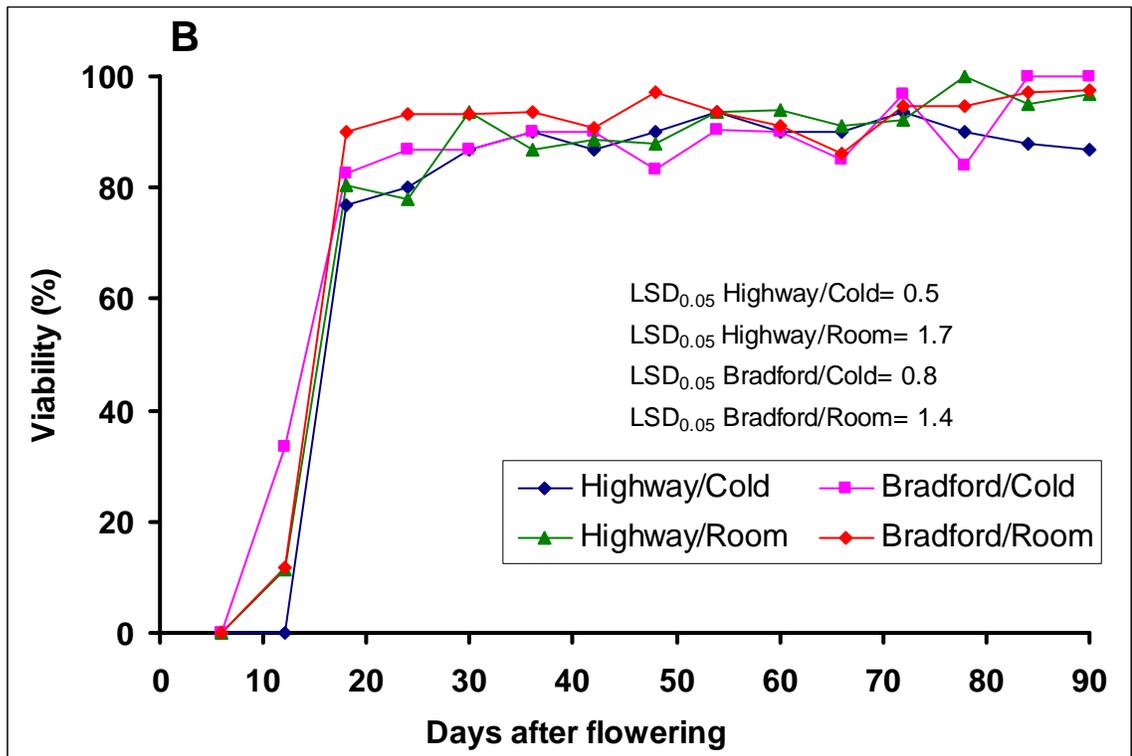
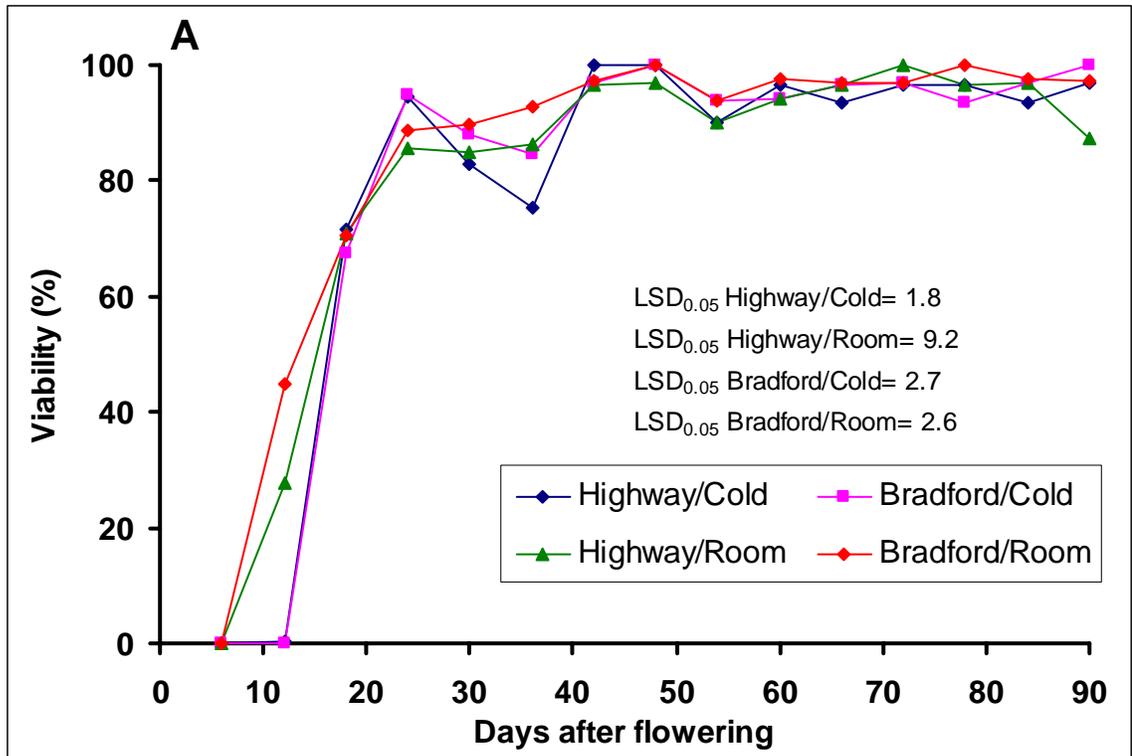


Figure 2.5. Cut-leaved teasel (*Dipsacus laciniatus* L.) viability at different periods after flowering. Seed stored at room and cold conditions from samples harvested in 2004 (A) and 2005 (B) for Bradford and Highway, MO.

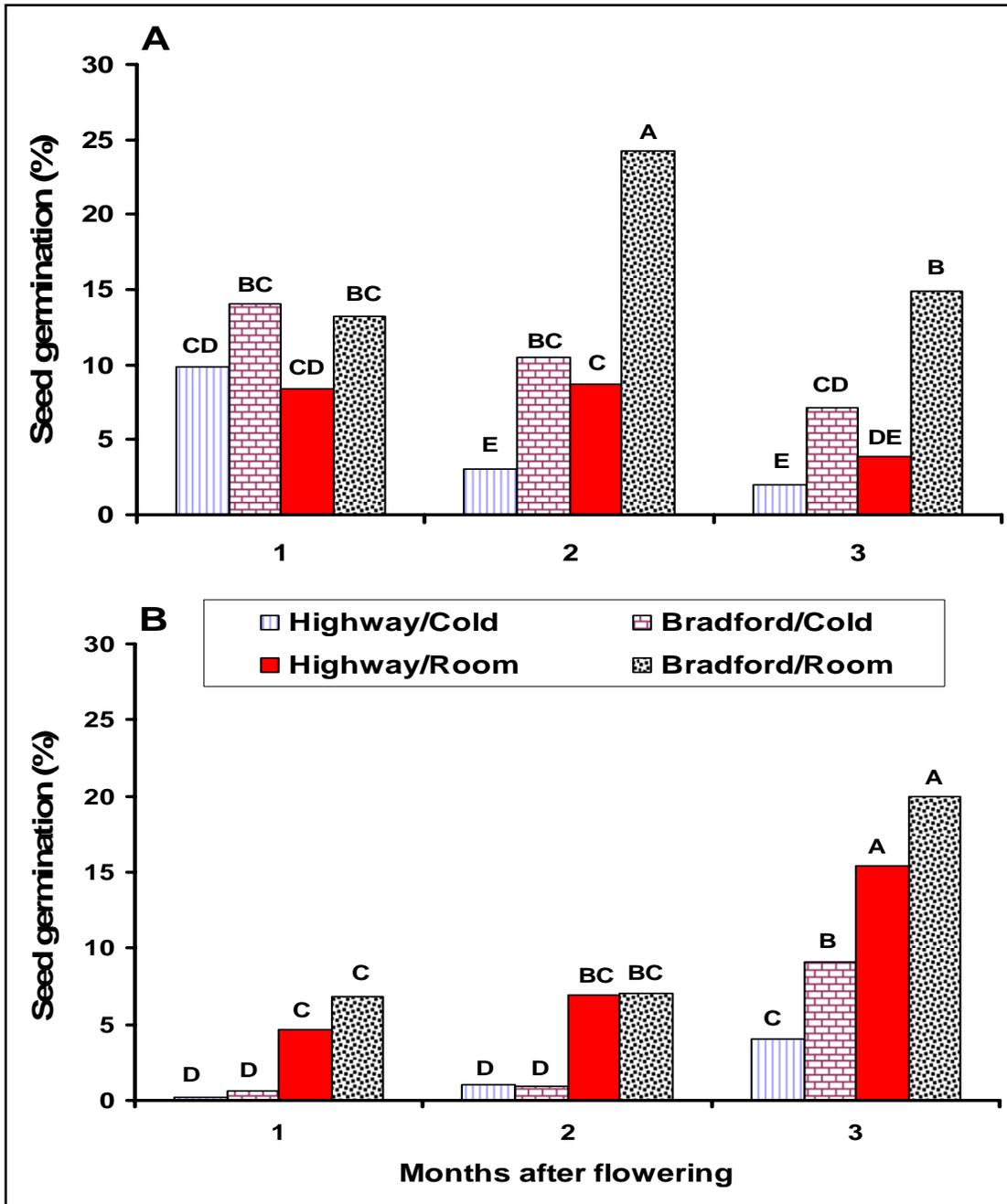


Figure 2.6. Means cumulative germination of cut-leaved teasel (*Dipsacus laciniatus* L.) harvested at various times following flowering. Seeds were harvested in 2004 (A) and 2005 (B) from two locations (Bradford and Highway 63) in central Missouri, and stored under cold (4 C) and room temperature (18 to 22 C) conditions. Means with the same letter were not different according to Fisher's Protected LSD at $p \leq 0.05$.

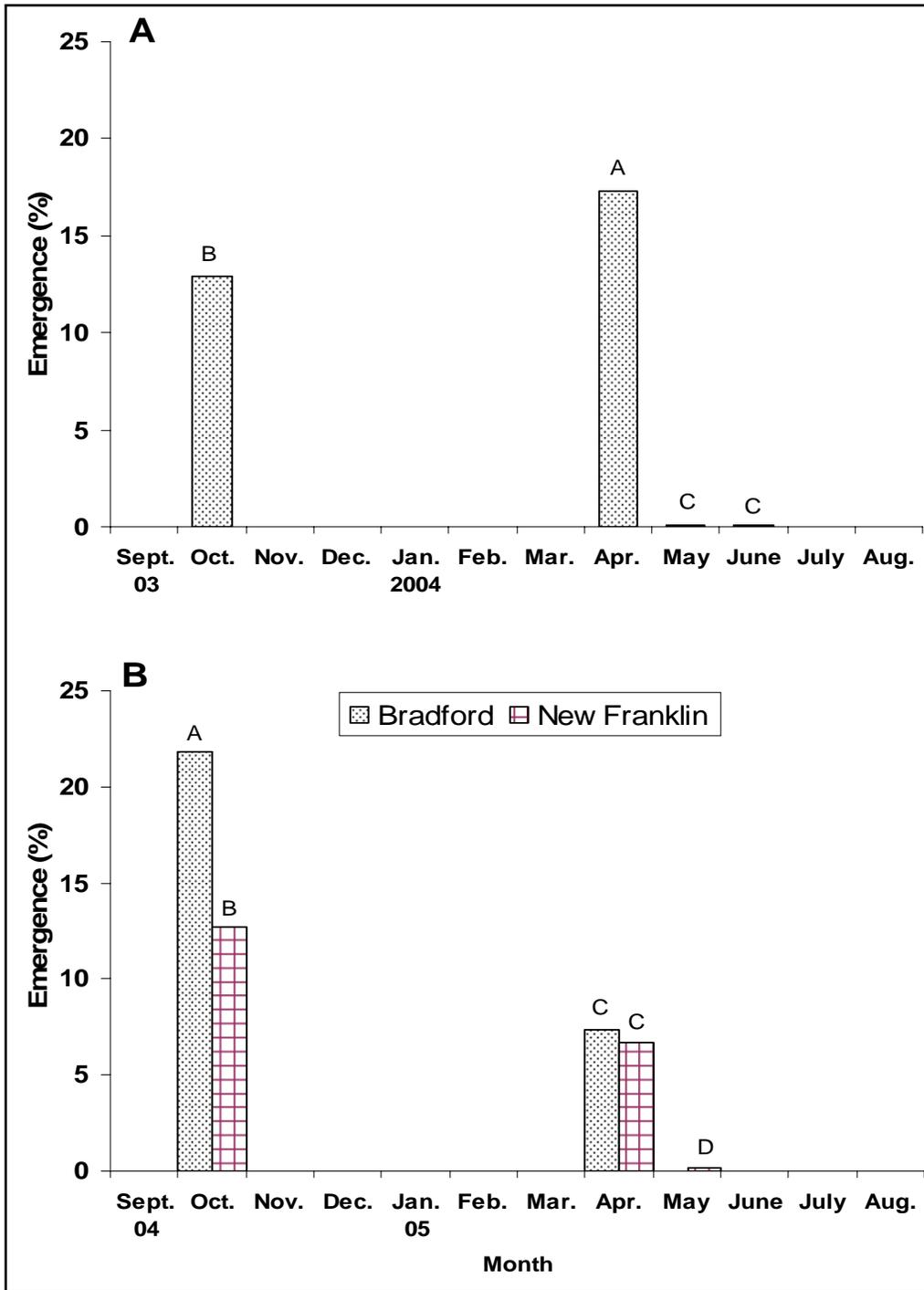


Figure 2.7. Cut-leaved teasel (*Dipsacus laciniatus* L.) emergence in central Missouri from 2003 to 2004 (A) at Bradford, and 2004-05 at Bradford and New Franklin (B), Letters within years were not statistically different according to Fisher Protected LSD $p \leq 0.05$.

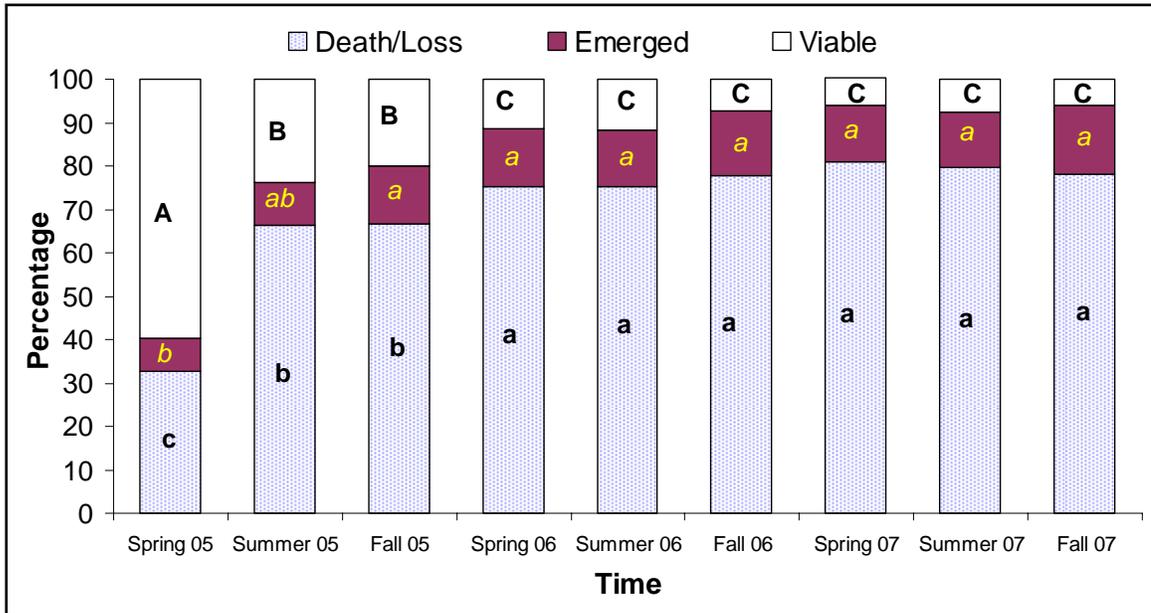


Figure 2.8. Accumulated seed germination, viability, and death/loss of cut-leaved teasel (*Dipsacus laciniatus* L.) collected over a period of three years. Data combined over two locations in central Missouri (New Franklin and Bradford). Means with the same letter inside each variable were not different according to Fisher's Protected LSD at $p \leq 0.05$.

CHAPTER III

Detecting Cut-leaved Teasel (*Dipsacus laciniatus* L.) along Missouri Highways using Hyperspectral Imagery

Abstract. Cut-leaved teasel is an invasive weed that poses a significant threat to native species along roadsides in Missouri. It is a biennial plant that grows as a rosette the first year and bolts the second. Flowering plants, together with understory rosettes, often grow in dense patches. Detection of cut-leaved teasel patches and accurate assessment of the area infested can enable targeted management along highways. Few studies have identified specific species among a complex of species along a roadside. In this study, hyperspectral images (63 bands) with high spatial resolution (1 m) were analyzed to detect cut-leaved teasel in two areas (Exit 89 and Lamine) along a four-mile section of Interstate (I-70) in Mid-Missouri . Identified classes included: cut-leaved teasel, bare soil, tree/shrub, grass/broadleaf plants, and water. Cut-leaved teasel user's classification was 82% accurate for the Exit 89 site and 84% accurate for the Lamine site. This resulted in a map that classified cut-leaved teasel distribution. The image classified teasel map provides a practical mechanism to identify the locations and extents of teasel infestation so that specific teasel management techniques can be implemented.

Nomenclature: teasel, *Dipsacus laciniatus* L, invasive, roadside, DIWLA¹.

Additional Index Words: cut-leaved, hyperspectral, weed detection.

¹ USA code for *Dipsacus Laciniatus* L. in WSSA-approved *Composite List of Weeds*. Revised 2008. WSSA 810 East 10th street, Lawrence, KS 66044-8897.

INTRODUCTION

Management of invasive weeds is a major challenge for land managers, due primarily to limited resources and diverse patterns of weed distribution. Invasive weeds are highly competitive and spread quickly in many habitats (Czarapata 2005). Weeds are not homogenously distributed in natural areas. In contrast, they are often aggregated in patches according to seed dispersal, soil adaptation, microclimate and topography (Shaw 2005a).

Cut-leaved teasel (*Dipsacus laciniatus L.*) is an invasive, noxious weed in Missouri. Biennial plants grow as a rosette in the first year following emergence and bolt after a cold period (winter) One single flowering plant may produce over 33,000 seeds per year (Bentivegna 2006), which are dispersed up to 1.5 meters around parent plants (Werner 1975). Seed dispersal can also be facilitated by mowing or floating in water (Solecki 1993). As flowering plants die, existing rosettes become established and new seedlings emerge in infested areas and also in areas where seed have been spread. Rosette plants produce a dense canopy that ultimately excludes desirable species.

Dense patches of cut-leaved teasel aggressively colonize low maintenance areas such as roadside right-of-ways which often serve as seed dispersal corridor (Solecki 1993; Hoffman and Kearns 1997). Tall flowering plants along highways can reduce traffic visibility and increase hazards to motorists (Rand Swanigan, personal communication²). Plants reduce the diversity of native desirable species such as tall

² Rand Swanigan. Head of Roadside Management and Maintenance for MoDOT.

fescue. Taproots of teasel reduce the infiltration of water, which increases water erosion compared to the presence of grasses (Lacey et al. 1989). As a result, cut-leaved teasel control is necessary to reduce negative affects along roadsides.

Typical management of cut-leaved teasel involves mowing and herbicide application. Mowing rosettes decreases the competitiveness of plants, but the time of mowing is critical. Plants mowed prior to flowering initiate new growth and produce viable seeds (Glass 1991). Mowing plants during flowering may enhance the dispersal of seeds (Cheesman 1998). Herbicides commonly used for teasel include growth regulators and acetolactate synthase inhibitors. These compounds are applied postemergence. To reduce the expense and environmental impacts by herbicides, site-specific herbicide application is often desirable, where only infested areas are treated (Saw 2005 a, 2005b). However, detection of cut-leaved teasel patches with ground surveys is time consuming and dangerous along high highways. For example, there are an estimated 40,000 vehicles per day that utilize Interstate 70 in Missouri (Rand Swanigan, personal communication⁴).

Remote sensing technology provides an effective method for large area detection of plants growing in distinct patches. Currently, aerial digital photographs in true color or color infrared have been used widely for the detection of plants with a unique spectral signature (Wang et al. 2008). Within the remote sensing area, these photos are also called multispectral images, with data recorded by only three or four spectral bands (visible-near infrared) are used to record data. Although these multispectral images could reach meter-scale resolution or higher, their use to identify specific weed species in heterogeneous landscapes is limited, due primarily to large variation in plant species, phenology, and mineral conditions (Lawrence et al. 2006).

Hyperspectral remote sensing can record spectral data in the visible-infrared region at much higher dimensions than multispectral images. Instead of three to four broad bands from typical aerial images, hyperspectral images generate hundreds of bands at narrow bandwidths in the same spectral region. These narrow band images can discriminate the subtle spectral differences between weeds and native species, which improve the capability of separating target plants from other species (Lass et al. 2002). In past studies, hyperspectral imaging has been used to detect non-native species such as iceplant (*Carpobrotus edulis*) (Underwood et al. 2003), spotted knapweed (*Centaurea maculosa* Lam.) (Lass et al. 2002; Lawrence et al. 2006), horse tamarind (*Leucaena leucocephala* Lam.) (Tsai and Chen 2004), and sericia lespedeza (*Lespedeza cuneata* Dum.-Cours.) (Wang et al. 2007).

Former studies were conducted in relatively homogeneous landscapes such as croplands and pastures. Currently, there is no documented information regarding weed detection with remote sensing techniques in highly heterogeneous environments such as roadsides. The objective of this research was to test the validity and accuracy of mapping cut-leaved teasel patches using hyperspectral imagery along Interstate 70 in Mid-Missouri.

MATERIALS AND METHODS

Study area and vegetation description

Two sections along Interstate Highway I-70 in Cooper County, MO were selected as study areas. One was around Exit 89 and the other was close to Lamine River crossing

the highway (mile markers from 89 to 93). These two sites were thus called Exit 89 and Lamine in the following context. Soils at these sites were a Winfield silt loam (Fine-silty, mixed, superactive, mesic Oxyaquic Hapludalfs) and a Bluelick silt loam (Fine, mixed, superactive, mesic Typic Paleudalfs) (NRCS 2008). Tall fescue (*Festuca arundinacea* Schreb.) was the desired and dominantly established plant along I-70. Cut-leaved teasel heavily invaded both sites. Other undesirable species included Sericia lespedeza, johnsongrass (*Sorghum halepense* L.) and common milkweed (*Asclepias syriaca* L.). Some brushes and tree species such as oak (*Quercus sp.*) hickory (*Carya sp.*) and pine (*Pinus echinata*) were also observed.

A reference site with pure stands of cut-leaved teasel was established at the Bradford Research and Extension Center (BREC), located 64 km east of the Lamine site. The soil type at BREC was a Mexico silt loam (Fine, smectitic, mesic Vertic Epiaqualfs) (NRCS 2008). The BREC site was composed of cut-leaved teasel and Missouri goldenrod (*Solidago missouriensis* Nutt.). Both stands of pure rosette and flowering plants could be located at the BREC site.

Data collection

At 10:00AM to 2:00PM on July 25, 2006, three hyperspectral images were acquired by personnel from the Center for Advance Land Management Information Technologies (CALMIT) at the University of Nebraska-Lincoln and Aviation Institute of the University of Nebraska-Omaha. These institutions are known as the Nebraska Airborne Remote Sensing Program (NARSP). The platform of the sensor was a Piper Saratoga aircraft (N186CA). The hyperspectral image was collected from the AISA

(Airbone Imaging Spectroradiometer for Application) sensor, a pushbroom imaging spectrometer built by Specim Ltd. Company³. The flight height was 1,538 m above ground level. Each image contained 63 bands at 9.8 nm bandwidth in spectral region of 401 to 981 nm (visible-near infrared), with a pixel size of 1 m.

Skies were clear during the flight time. Average weather conditions were 32 C air temperature, 39% relative humidity, 4 m s⁻¹ wind speed, and 815 wattm⁻² radiation. The AISA images delivered by CALMIT were corrected radiometrically, atmospherically, and geometrically. The digital number of each pixel represented surface reflectance. To reduce data storage space and computation time, subsets of AISA images over the two study sites were clipped using “subset data via ROI” procedure in ENVI (ENVI 2006). The AISA images at the Exit 89 and Lamine sites are shown in Figure 3.1. Areas of grass were more evident at the Exit 89 site compared to the Lamine site, with more tree/shrub patches observed at the Lamine versus Exit 89 site.

A field survey was conducted in the day prior to the flight to locate patches of cut-leaved teasel. In addition, GPS data were recorded in the areas with the highest infestation level. Others species present were also recorded in the area of study.

Image classification

The highway environment was represented by a unique dynamic of land cover patches, which were categorized as tall fescue, cut-leaved teasel, and other plant species such as shrubs and trees. For patches with same vegetation types at different locations, the spectral response could be distinctively different depending upon variation in plant height and density, soil fertility, and water availability. For this reason, it was difficult to

³ Specim Ltd. Company. POB 110. Teknologiantie 18A. Oulu, 90571., Finland.

identify representative training data sets in the AISA images at both study sites. A stepwise, unsupervised/supervised classification algorithm was applied in this study to extract cut-leaved teasel patches in multi-step image processes without *a priori* information of land cover categories on the ground.

Unsupervised classification did not require ground trusting, for training data to recognize different land covers. Rather, this technique defined criteria for classification based upon statistical or graphical properties of all pixels in the image (Jenson 2004). With a pre-defined number of clusters, pixels fell in the criteria for each assigned cluster. As a result, unsupervised classification is a common method to obtain land covers in irregular environments with little training data (Schowengerdt 2007). As a commonly applied unsupervised classifier, the ISODATA (Iterative Self-Organizing Data Analysis Techniques) module in ERDAS Imagine V9.0⁴ was performed. Based on iterative optimization of spectral distances from cluster means, a total of 300 clusters were assigned to each AISA image. The convergence threshold was determined as 0.95, which is the maximum amount of pixel not permitted to change between interactions. Based upon the analyzer's familiarity with study sites obtained during field surveys, the clusters were visually examined in the AISA image and re-grouped into 20 classes. Each class represented a unique land cover type for a site. The spectral signatures of these 20 classes were also saved in this step.

Assuming the spectral signatures represented training data, the maximum likelihood classifier (MLC), a most commonly applied supervised classification algorithm, was then performed on the AISA images. The MLC calculated n-space (n represented band

⁴ ERDAS Imagine 9. Worldwide headquarters 5051 Peachtree Corners Circle Norcross ,GA, 30092-2500.USA

numbers) variance and covariance to build the probability density function of each class. The pixel was assigned to the class with highest probability. Although mathematically complex and computationally slower, the MLC provided more accurate classifications than the ISODATA algorithm, which was based simply upon in-band mean with a standard deviation.

Since cut-leaved teasel was the major target species in this study, the 20 classes after the unsupervised/supervised process were re-grouped into cut-leaved teasel, water, bare soil, tree/shrub, and grass/broadleaf. Finally, a 5 by 5 majority filtering process was conducted to reduce noises in the classified patches (Lass et al. 2002; Okamoto et al. 2007).

Accuracy assessment

Cut-leaved teasel patches were located during field surveys and their GPS coordinates recorded. Random patches of other classes, such as bare surface, water, grass/broadleaf, and trees could be easily identified via visual interpretation in the 50 cm true-color aerial photo taken in 2007. These data were assumed ground truth to assess the accuracy of the class maps. With a stratified random sampling rule (Congalton and Green 1999), 50 points for each class (cut-leaved teasel, water, bare soil, tree/shrub, and grass/broadleaf) were extracted and compared during construction of an error matrix (Table 3.1). The overall accuracy, producer's accuracy, and user's accuracy of the classification was then calculated (Congalton and Green 1999; Jensen 2004).

The overall accuracy was the ratio between the number of correct points (all classes from the ground survey that were correctly identified) and all points used in the

assessment (250 in this study). The level of accuracy explained the general agreement between all image-based classes and ground data. However, because the focus of this study was on cut-leaved teasel mapping, the overall accuracy reflected misclassification of all classes.

Producer's and user's accuracies were better applied in examining the accuracy of a specific class. For each class, producer's accuracy was the ratio between the number of correct points and all points that were assigned a specific classification from the image. Producer's accuracy was also a measure of omission error, indicating the underestimation that a patch was not identified in the classification. User's accuracy, on the other hand, was the ratio between the number of correct points and all points that truly belonged to a specific class (ground truth). Therefore, user's accuracy was a measure of commission error, the overestimation for assigning a patch to an improper class. Producer's and user's accuracies of cut-leaved teasel explained the underestimation and overestimation of image-based teasel mapping in this study.

Another commonly applied technique of accuracy assessment was Kappa analysis. Kappa Coefficient of Agreement (Kappa value) is a multivariate statistic used to measure the agreement between image-derived classification and reference data. The range of Kappa value is from 0 to 1. A larger Kappa value indicates greater accuracy for the overall classification. Similarly, for each class, the conditional Kappa value was calculated as a measure of classification accuracy of a specific class. These variables of accuracies and Kappa values provided a way to quantitatively evaluate the creditability of remote sensing techniques in plant mapping.

RESULTS AND DISCUSSION

At the time of acquiring the AISA image, cut-leaved teasel patches along I-70 were composed of tall flowering plants (2.2 m) and understory rosettes. While flowering plants were not significantly shading understory plants (Werner 1977), rosettes intercepted up to 95% of the light (Bentivegna 2006). The spectral characteristics of flowering and rosette plants could be different based upon photosynthetic rates and light interception. Consequently, the spectra of cut-leaved teasel patches varied with the mixed composition of flowering and rosette plants.

One sample patch of cut-leaved teasel was selected and the absorption spectrum extracted from the AISA image at the Exit 89 and Lamine sites respectively. These spectra were a mixture of flowering and rosette plants. As reference spectra, examples of pure rosette and flowering plants (Figure 3.1) were also extracted at the BREC site (Figure 3.2). The spectral signature of cut-leaved teasel was extracted for each location (Figure 3.3). It was possible to determine reflectance of rosettes in a pure stand of cut-leaved teasel at Bradford (Figure 3.3). Flowering plant (flowering+ rosette) at Exit 89 and Lamine were also displayed (Figure 3.3). Differences in the spectral signatures of cut-leaved teasel were evident between the BREC site and along I-70. Mature plants at the BREC site were fully flowering, while highway plants had completed flowering. In addition, plants at the BREC site were represented as pure patches of rosette and flowering plants compared to a mixture of flowering and rosette plants along I-70. Cut-leaved teasel at the BREC site compared to the I-70 site was established on a more productive soil, which resulted in more fertile plants with less overall stress. As a result,

cut-leaved teasel at the BREC site exhibited a stronger spectral response than plants at the Exit 89 and Lamine sites. This was demonstrated by spectral difference in Figure 3.2 could also be explained with plant physiology. Rosette plants at the BREC site reflected less green (bands 17-18) and far less red light (bands 30-32) compared to flowering plants, suggesting rosette plants were more photosynthetically active. Cut-leaved teasel at the Exit 89 and Lamine sites exhibited a pattern of spectral reflectance. The visible-band reflectance (band 1 to 32) at the Exit 89 site was slightly higher and the near-infrared reflectance (band 33 to 63) was slightly lower compared to the Lamine site. This may indicate that the sampled cut-leaved teasel patch at the Lamine site contained a greater level of coverage with rosette plants. Flowering plants at the highway sites had similar spectral reflectance (Figure 3.3). A sample four classes supervised classification was performed in the AISA image at Bradford field (Figure 3.4). There was a strong absorption in the red band (28-31) for rosette plants, which suggests high absorption by the chlorophylls in dense leaves of these plants (Jensen 2007). Also, flowering plants at Bradford displayed slightly less photosynthetic activity than rosette plants.

After re-grouping the 300 clusters from unsupervised classification of the AISA images, spectra of the 20 representative classes (in 5 land cover types) are shown in Figure 3.3. Due to a heterogeneous landscape along the highway environment, multiple classes were often selected in one land cover type. Grasses and trees were dominant land cover types in both images. At the Exit 89 site, there were 10 grass/broadleaf classes, four tree/shrubs, three bare soils, two waters, and 1 cut-leaved teasel class as training data sets. At the Lamine site, there were eight tree/shrub classes, seven grass/broadleaves, two bare

soils, one water, and one cut-leaved teasel class as training data sets. The class map was then developed using the training data by an supervised classification method (MLC).

As shown in the class map (Figure 3.5), most cut-leaved teasel patches were detected up to 4.5 meters from the pavement of I-70. The Exit 89 sites had three-fold more pixels of cut-leaved teasel than the Lamine site. MoDOT frequently mows the center median and the first 4.5 meters along the edge of the east and west-bound lanes. Therefore cut-leaved teasel is not likely survive in these areas. The majority of cut-leaved teasel patches were observed along the roadside where slopes were often steeper than 18°, and where rocks were present. In these areas, human disturbance is limited and therefore, mowing is not possible. For management of teasel in these areas, establishment of competitive, desirable plants or repeated application of selective herbicides is necessary.

In the error matrices of classification at the Exit 89 (Table 3.1) and the Lamine site (Table 3.2), the overall accuracy of AISA image classification, when all of the five land cover categories were considered, was 92% and 90%, respectively. The Kappa value was approximately 0.9 at each study site. With the exception of the grass/broadleaf class at the Lamine site, the non-teasel classes had omission errors <10%. In other words, more than 90% of the 50 reference points were identified correctly. Grass/broadleaf at both sites was the class that was most likely to be overestimated. For example, at the Exit 89 site (Table 3.1), 55 points were classified as grass/broadleaf, while only 47 from ground surveys belonged to this class. At the Lamine site, 53 were classified as grass/broadleaf while only 42 from ground surveys belonged to this class.

Cut-leaved teasel was classified from the AISA images with omission and commission errors in a range of 10 to 18% at both sites. The misclassification primarily resulted from confusion with grass/broadleaf. At the Exit 89 site, five teasel points were misclassified as grass/broadleaf (underestimation) and two grass/broadleaf points were misclassified as teasel (overestimation). At the Lamine site, the underestimation was eight points, while the overestimation reached 5 points, with all points confused with grass/broadleaf points. The misclassification between cut-leaved teasel and grass/broadleaf may be based upon mixed pixels in the AISA images. Cut-leaved teasel along I-70 often grows in narrow and long patches. As a result, in the AISA images at the one meter pixel size were sometimes a mixture of cut-leaf teasel with desirable species such as grasses.

Misclassification of cut-leaved teasel may also stem from the temporal variation between AISA image acquisition and the ground reference data collected and used for accuracy assessment. Although cut-leaved teasel reference points were located during field surveys at the time of the AISA flight, other reference data were collected in an aerial photo acquired in spring 2007, almost one year after the AISA image was acquired. Land cover may vary in this period. Some cut-leaved teasel patches may have been mowed or treated with herbicides. It is also possible that some teasel plants died, resulting in the replacement by other species or remaining as bare soil.. Some cut-leaved teasel patches were located in rocky areas, and this may have affected teasel detection. In fact, four pixels were classified at the Exit 89 site as bare soil, but pixels from ground surveys were observed to contain teasel.

In a heterogeneous species environment along a highway, the multi-step unsupervised/supervised mapping of an invasive weed was comparable to results from other studies. Using hyperspectral images, Lawrence et al. (2006) identified spotted knapweed and leafy spurge with 76 and 79% of user accuracy, respectively, at different sites in Montana. Ustin et al.(2002) was able to detect *Arundo donax* using maximum likelihood classified with an accuracy of 97.8% in California.

Hyperspectral remote sensing provides an effective method for mapping cut-leaved teasel over a large area along an interstate highway. Most of the plant was mapped close to the highway which confirms that it is common environment for this invasive plant. However, despite advances in sensor technology and greater computer storage capability for processing images, hyperspectral images are difficult to work with because of the large image sizes. Reducing the number of bands is useful for the removal of redundant spectral bands and for reducing the size of hyperspectral images. Also, together with the increased interest in hyperspectral image applications, more image processing and classification methods are being improved for detection of target species. A comparison of these approaches could lead to the identification of a classification method that is adaptable for the detection of a target species along a complex highway environment.

LITERATURE CITED

- Bentivegna, D.J. 2006. Biology and management of cut-leaved teasel (*Dipsacus laciniatus* L.) in central Missouri. M.S. Thesis University of Missouri. 67 p.
- Campbell, J.B. 2002. Introduction to Remote Sensing. The Guilford press, New York, NY. 620 p.
- Carson, H. W., L. W. Lass, and R. H. Callihan 1995. Detection of yellow hawkweed (*Hieracium pretense*) with high resolution multispectral digital imagery. Weed Technology 9:477-4783.
- Cheesman, O.D. 1998,. The impact of some field boundary management practices on the development of *Dipsacus fullonum* L. flowering stems, and implication for conservation. Agriculture, Ecosystems and Environment 68:41-49.
- Congalton, R.G. and K. Green. 1999. Assessing the Accuracy of Remote Sensed Data: Principles and Practices. Lewis Publishers,.Boca Raton. FL. 137 p.
- Czarapata, E.J. 2005. Invasive Plants of the Upper Midwest : An Illustrated guide to their identification and control. The University of Wisconsin Press. Madison, WI. 215 p.
- ENVI. 2006. The environment for visualizing images. ENVI Tutorials, version 4.3. Research System Institute, USA.
- ERDAS Image. 2005. ERDAS Field Guide[™]. Version :ERDAS 9. Leica Geosystems Geospatial Imaging, LLC. 705 p.

- Glass, W.D. 1991. Vegetation management guideline: Cut-leaved teasel (*Dipsacus laciniatus* L.) and common teasel (*Dipsacus sylvestris* Huds.). *Natural Areas Journal* 11:213-214.
- Hoffman, R. and K. Kearns. 1997. Wisconsin manual of control recommendation for ecologically invasive plants. Wisconsin Department Natural Resources, Madison, WI. 102 p.
- Jensen, J.R. 2004. *Introductory Digital Image Processing*. ed Prentice Hall. Upper Saddle River, NJ. 544 p.
- Jensen, J.R. 2007. Remote sensing of Vegetation. *in: Remote Sensing of the Environment*. ed. Prentice Hall. Upper Saddle River, NJ. Pp. 355-400.
- Lacey, L.W., C.B. Marlow, and J.R. lane 1989. Influence of spotted knapweed (*Centaurea maculosa*) on surface runoff and sediment yield. *Weed Technology* 3:627-631.
- Lass, L.W., D.C. Thill, B.Shaffii, and T.S. Prather. 2002. Detecting spotted knapweed (*Centaurea maculosa*) with hyperspectral remote sensing technology. *Weed Technology* 16:426-432.
- Lawrence, R.L., S.D. Wood , and R.L. Sheley. 2006. Mapping invasive plants using hyperspectral imagery and Breiman Cutler classifications (RandomForest). *Remote Sensing of Environment* 100:356-362.
- NRCS. 2008. Natural Resources Conservation Service. United States Department of agriculture. Official Soil Series Descriptions. <http://soils.usda.gov/technical/classification/osd/index.html> [Accessed 15 February 2008]. USDA-NRCS.Lincoln, NE.

- Schowengerdt, R.A. 2007. Remote Sensing. Model and methods for image processing. Elsevier press. London, UK. 516 p
- Shaw, D.R. 2005a. Remote sensing and site-specific weed management. *Frontier in Ecology and the Environment*. 3:526-532.
- Shaw, D.R. 2005b. Translation of remote sensing data into weed management decisions. *Weed Science* 53:264-273.
- Solecki, M.K. 1993. Cut-leaved and common teasel (*Dipsacus laciniatus* L and *D. sylvestris* Huds.): profile of two invasive aliens. *in* McKnight, B.N. ed. *Biological Pollution: The control and impact of invasive exotic species*. Indiana Academic of Science, Indianapolis, IN. Pp. 85-92.
- Okamoto, H., T. Murata, T.Kataoka, and S.Hata. 2007. Plant classification for weed detection using hyperspectral imaging with wavelet analysis. *Weed Biology and Management* 7:31-37.
- Tsai, F. and C. Chen. 2004. Detecting invasive plants using hyperspectral and high resolution satellites images. XXth Proceedings of International society for photogrammetry and remote sensing. Istanbul, Turkey. 14.
- Underwood, E., S.Ustin and D DiPietro. 2003. Mapping non-native plants using hyperspectral imagery. *Remote Sensing of Environment* 86:150-161.
- Ustin, S.L., K. DiPietro, K.Olmstead, E. Underwood, and G.J. Scheer. 2002. Hyperspectral remote sensing for invasive species detection and mapping. *International Geoscience and Remote Sensing Symposium*. Toronto, Canada. 3:1658-1660.

- Werner, P.A. 1975. A seed trap for determining patterns of seed deposition in terrestrial plant. *Canadian Journal of Botany* 53:810-813.
- Werner, P.A. 1977. Colonization success of a “biennial” plant species: experimental field studies of species cohabitation and replacement. *Ecology* 58:840-849.
- Wang, C., B. Zhou, and H. L. Palm, 2008. Detecting invasive sericea lespedeza (*Lespedeza cuneata*) in Mid-Missouri pastureland using hyperspectral imagery. *Environmental Management* 41:853-862.

Table 3.1. Error matrix, producer's, and user's accuracy of the maximum likelihood classification of AISA-based class map at the Exit 89 site, Cooper County, Missouri.

	Cut-leaved teasel	Water	Bare Soil	Tree + shrub	Grass+ Broadleaf	Row Total
Cut-leaved teasel	41		4		5	50
Water		50				50
Bare Soil	2		46		2	50
Tree+ shrub	1			47	1	50
Grass+ Broadleaf	2		1		47	50
Column Total	46	50	51	47	55	250

Class	Producer's accuracy	User's Accuracy
Cut-leaved teasel	89.1	82
Water	100	100
Bare Soil	90.2	92
Tree+ shrub	100	94
Grass+ Broadleaf	83.9	94
Overall accuracy		92.4
Kappa coefficient		0.91

Table 3.2. Error matrix, producer's, and user's accuracy of the maximum likelihood classification of AISA-based class map at the Lamine site, Cooper County, Missouri.

	Cut-leaved teasel	Water	Bare Soil	Tree + shrub	Grass+ Broadleaf	Row Total
Cut-leaved teasel	42				8	50
Water		45		5		50
Bare Soil			47	1	2	50
Tree+ shrub				49	1	50
Grass+ Broadleaf	5		2	1	42	50
Column Total	47	45	49	56	53	250

Class	Producer's accuracy	User's accuracy
Cut-leaved teasel	89.4	84
Water	100	90
Bare Soil	95.9	94
Tree+ shrub	87.5	98
Grass+ Broadleaf	79.3	84
Overall accuracy	90	
Kappa coefficient	0.88	

A)



B)



210 0 210 420 Meters

Figure 3.1. AISA images at the Exit 89 (A) and the Lamine site (B), acquired on July 25, 2006, Cooper County, MO. The R, G, B composition was 472, 544, and 638 nm wavelength for each layer.

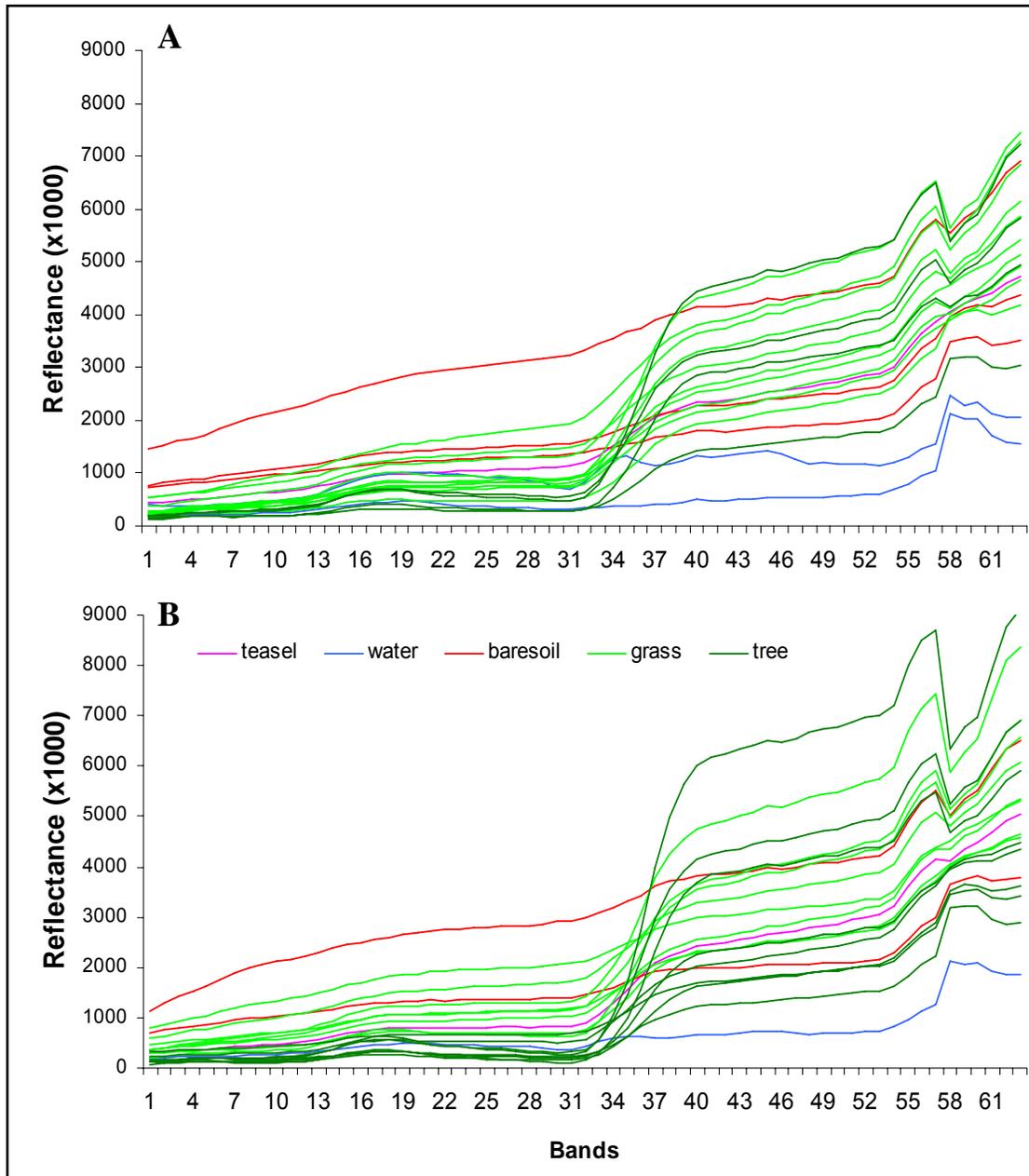


Figure 3.2. Spectra of the 20 representative classes at the Exit 89 (A) and Lamine site (B) in Cooper County, MO on July 25, 2006.

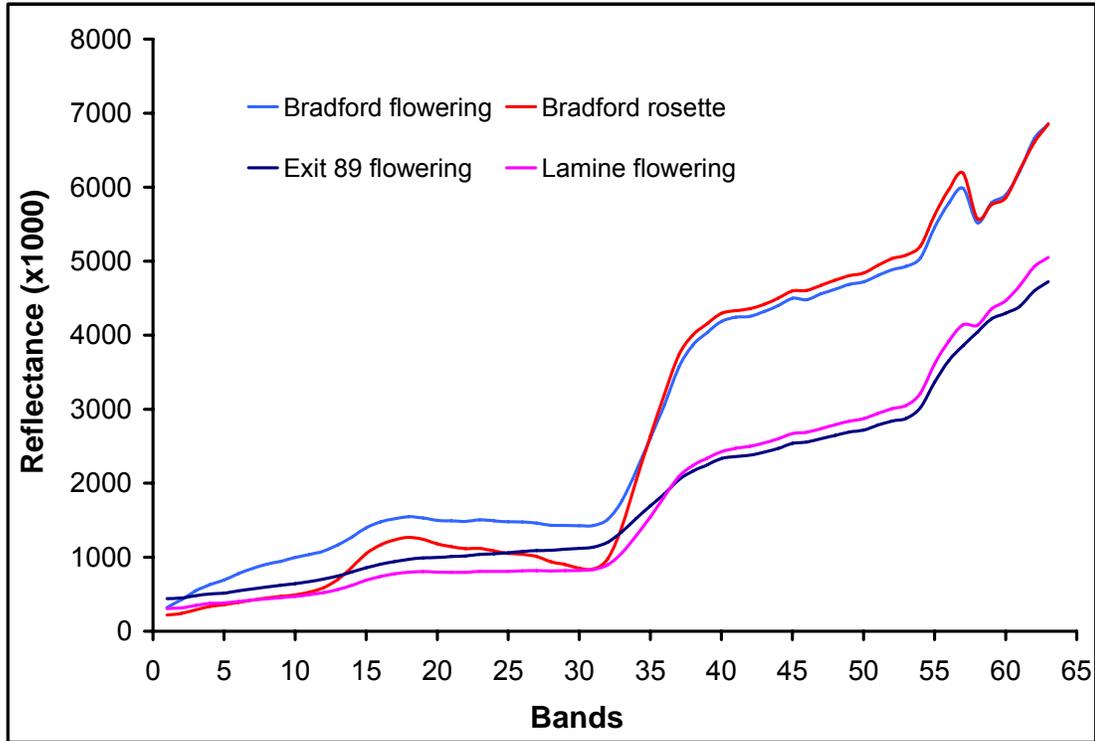
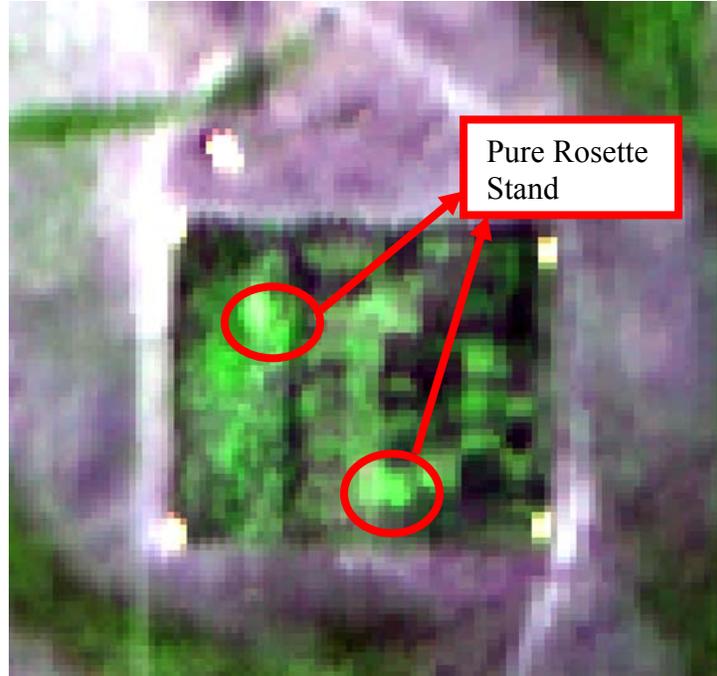
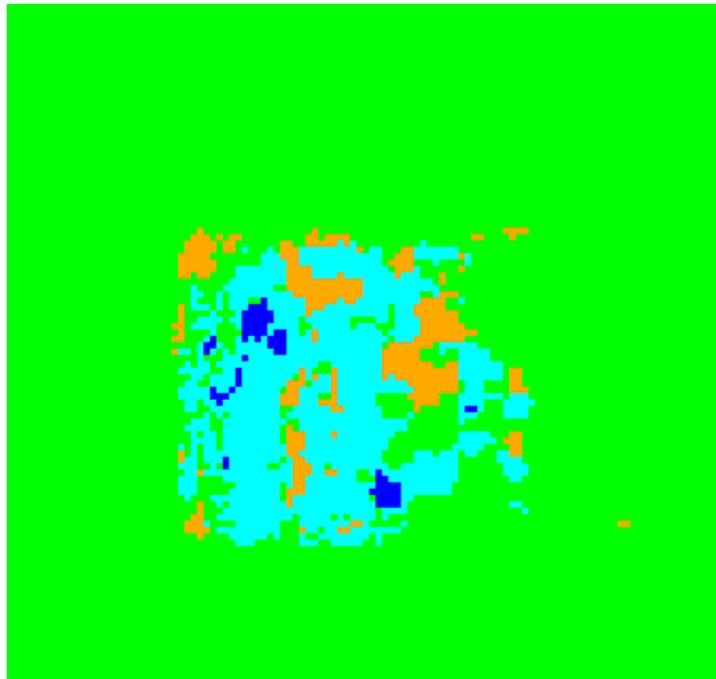


Figure 3.3. Spectra of sampled patches of pure rosettes and flowering plants at the BREC site as well as mixed flowering and rosette plants at the Exit 89 and Lamine sites.

A



B



■ Flowering ■ Rosette Teasel
■ Others ■ Grass and Grass plus Broadleaf

Figure 3.4. Images of the cut-leaved teasel plot taken on July 25, 2006 at the Bradford Research and Extension Center, Boone County, MO. Images were composed of Red-Green-Blue bands (A) and a classification map (B).

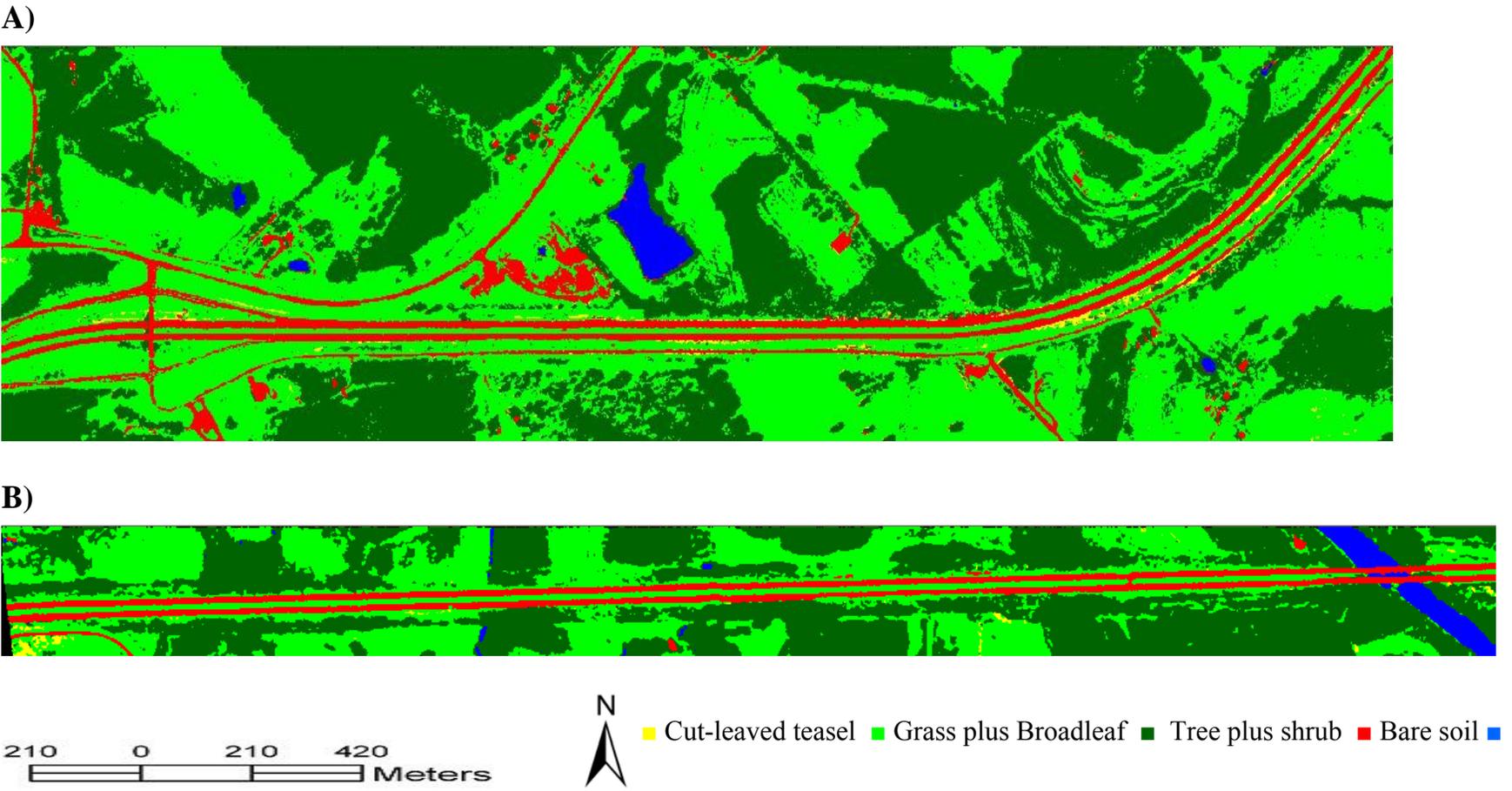


Figure 3.5. Class maps at the Exit 89 (A) and the Lamine site (B) at Cooper County, MO for July 26, 2006.

CHAPTER IV

Comparing classification methods for mapping cut-leaved teasel (*Dipsacus laciniatus* L.) along Missouri highways with hyperspectral imagery

Abstract: Cut-leaved teasel is an invasive plant that thrives in roadside environments. Plants reproduce by seeds and their distribution around the parent plant results in dense patches. Site-specific management of cut-leaved teasel requires precise location of the patches for the application of herbicides. Remote sensing provides an efficient way to map teasel populations in large and complex roadside environments. In this study, two aerial hyperspectral images (AISA) were utilized to test the validity and accuracy of detecting cut-leaved teasel along Interstate 70 in Mid-Missouri by comparing different classification approaches. Twenty spectral signatures were selected by re-grouping the 300 clusters from an unsupervised classification and were used as training data. The maximum likelihood classifier (MLC) and spectral angle mapper (SAM) approaches were imposed on the AISA images over two study sites to run a 5-class supervised classification. The MLC and SAM were also performed with images represented by only 12 optimal bands. This study demonstrated that the MLC approach could better identify cut-leaved teasel in roadside environments than SAM. Band reduction from 63 to 12 bands reduced the accuracy of cut-leaved teasel mapping in a heterogeneous landscape and therefore, may not be advantageous for weed detection along highways.

Abstract: Nomenclature: cut-leaved teasel, *Dipsacus laciniatus* L, invasive, roadside.

Additional Index Words: classifier, hyperspectral, maximum likelihood, spectral angle mapper.

INTRODUCTION

Cut-leaved teasel (*Dipsacus laciniatus* L.) is an invasive weed that infests roadside environments (Solecki 1993). It is a biennial plant that grows as a rosette the first year and bolts the second year (Werner 1975a). Plants have lanceolate, sessile, serrate leaves which result in a leaf area index up to 3.1 in the rosette stage, providing a competitive advantage over native species (Bentivegna 2006). One plant is able to produce up to 33,500 seeds, which are distributed around parent plants (Werner 1975b; Bentivegna 2006). Teasel patches are composed of flowering plants and understory rosettes.

Cut-leaved teasel patches reduce traffic visibility along roadside habitats and outcompete desirable grass species. Cut-leaved teasel has been declared a noxious weed in four states, including Missouri (USDA 2008). By law, noxious weeds must be controlled wherever found. The Missouri Department of Transportation (MoDOT) is responsible for management of cut-leaved teasel along roadside areas. However, it is difficult for MoDOT to implement management along an extensive road system. Medlin et al. (2000) and Shaw (2005) reported that mapping the areas of weed infestations would permit site-specific management (SSM) (e.g. mowing or applying herbicides) only in infested sites.

In-situ surveys with hand-held GPS receivers are time consuming and logistically impractical for larger areas and are extremely hazardous to highway workers. Remote sensing has been used to detect invasive plants in various environments (Lass et al. 2002, Lawrence et al. 2006, Tsai et al. 2007, Underwood et al. 2003, Wang et al. 2007). Cut-leaved teasel is a good candidate for remote sensing because it grows in compact patches and has a unique composition of rosette and flowering plants. White flowers of cut-leaved teasel could be observed in the second half of July in Missouri, creating a specific spectral response using remotely sensed imagery. The spectral difference between flowering plants and surrounding vegetation has been tested by Lass et al. (1996), who found that yellow starthistle (*Centaurea solstitialis*), which has yellow flowers, could be identified using remote sensing techniques.

Multispectral sensors mounted in aircrafts provide useful information in detecting weed species with distinctive spectral features at a particular time of the plants' life cycle (Lawrence et al. 2006, Nagendra 2001; Underwood et al. 2003). However, due to limited human management, land cover in roadside environments is often established naturally with a heterogeneous distribution of mixed vegetation growing in small patches. It is thus difficult to discriminate between plants with similar spectral responses in these typical broadband multispectral images. For this reason, narrow spectral bands are needed to identify the subtle spectral differences of vegetation types in mixed environments (Ustin et al. 2004).

Hyperpectral imagery contains up to hundreds of spectral bands with a narrow bandwidth of about 10 nm (Lass et al. 2002). At each pixel, images provide an almost continuous spectrum in the visible- infrared region (Aspinall 2002) and therefore, can

distinguish more spectra details to identify vegetation stands (Lawrence et al. 2006, Underwood et al. 2003, Ustin et al. 2004). Hyperspectral imagery has a high potential in identifying and mapping invasive plants as well as determining percent cover of species in sub-pixel size (Lawrence et al. 2006; Underwood et al. 2003).

Many different classification methods have been developed to map land use/land cover distribution using multispectral remote sensing imagery. Methodologies of supervised classification have been used to detect invasive plant patches (Lass et al 2005; Underwood et al. 2003). Among these methods, the one most commonly applied was the distance-based probability classifier, maximum likelihood classifier (MLC). MLC incorporates statistical properties (mean, variance, and covariance) of training data into decision rules (South et al. 2004; Underwood et al. 2003). Together with the increased interest in hyperspectral remote sensing, new classification methods are being developed to take advantage of nearly continuous spectra of training data sets. The spectral angle mapper (SAM), an angular-based classifier, treats the spectrum of each pixel as an n -dimension (n equals the number of bands) vector. Each pixel is assigned to a class that has the smallest angle with the reference vector (Schowengerdt 2007). Both MLC and SAM approaches have been applied to invasive species in certain environments using multispectral or hyperspectral imagery, in order to determine whether or not the weed is present or absent (Campbell 2002; South et al. 2004; Underwood et al. 2003).

When applied to hyperspectral imagery, the MLC approach is complex computationally especially when the in-band covariance is calculated for each pixel. The MLC method is sometimes restricted by the requirement that training data of each class are normally distributed. The SAM approach is of great advantage with hyperspectral

imagery. However, when comparing unknown spectra with reference ones, the angular calculation may be largely deviated in mixed pixels, which may result in large errors in classification. Mapping the same patches with different classification methodologies result in variable accuracy in the final map. For example, Shafri et al. (2007) reported that seven classes of trees were classified with 85% in MLC, but only 49% in SAM.

Taking into consideration the mixed species along a highway environment, the objective of this study was to compare the accuracy of MLC and SAM in detecting cut-leaved teasel along Interstate 70 in central Missouri. Both full bands (63) and the selected optimal bands (12) were processed to test the possibility and efficiency of cut-leaved teasel mapping with -reduced band hyperspectral images.

MATERIALS AND METHODS

Study area and vegetation description

Two sections of the Interstate Highway 70 (I-70) from mile marker 89 to 93 in Cooper County Missouri were selected. These sections were heavily infested with cut-leaved teasel (Figure 4.1). The first section was close to Exit 89 and adjacent Bryant Bottom Road, hereafter referred to as Exit 89 (38° 56' 49''W – 92° 58' 23''N). The second section was close to the Lamine River, hereafter referred as Lamine (38° 56' 1''W – 92° 57' 14''M). Soils were classified as a Winfield silt loam (Fine-silty, mixed, superactive, mesic Oxyaquic Hapludalfs) and Bluelick silt loam (Fine, mixed, superactive, mesic Typic Paleudalfs) (National Resources Conservation Service 2008). Areas were characterized as a roadside environment with rock present and steep slopes.

Tall fescue (*Festuca arundinacea* Schreb.) was the desirable grass species and was mixed with undesirable species such as Sericia lespedeza (*Lespedeza cuneata* Dum.-Cours.), johnsongrass (*Sorghum halepense* L.) and common milkweed (*Asclepias syriaca* L.). In addition, oak (*Quercus spp.*) hickory (*Carya spp.*) and pine (*Pinus spp.*) trees were also common.

Data collection

Two hyperspectral images were taken by the Center for Advance Land Management Information Technologies (CALMIT), affiliated with the University of Nebraska. A hyperspectral sensor was fixed to a Piper Saratoga aircraft which flew at an altitude of 1,538 m; the sensor had a total field-of-view of 9° across track. Images were collected by the sensor AISA (Airbone Image in Spectroradiometer for Application), which is a pushbroom imaging spectrometer built by Specim Ltd. Company.¹ The spatial resolution was 1 m. The AISA images collected contained 63 bands, ranging from 401 to 981 nm (visible and infrared spectrum), and a spectral resolution of 9.8 nm bandwidth. The images delivered by CALMIT had been atmospherically corrected using Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH), using an algorithm in Environmental Visualization Image (ENVI) (ENVI 2006). The images were also geometrically corrected by CALMIT to match ground reference.

Images were collected between 10 am and 2 pm on July 25, 2006. Weather conditions during the flight were: 32 C air temperature, 39% relative humidity, a 4 m s⁻¹ wind speed, and 815 watt m⁻² of radiation. Skies were clear and sunny. The images received from CALMIT contained reflectance for each pixel. To reduce data size as well

¹ Specim LTD. POB 110. Teknologiantie 18A. 90571. Oulu, Finland.

as computation time, images were reduced using the “subset data via ROI” procedure in ENVI and only subsets were processed in this study. The images of the two sections are shown in Figure 4.2.

Data processing techniques

The processing of hyperspectral images involved several steps: unsupervised classification (ISODATA), band reduction, supervised classification (MLC and SAM), and an accuracy assessment.

Unsupervised classification ISODATA (Iterative Self-Organizing Data Analysis Techniques) clustering was performed using ERDAS 9 (ERDAS 2005), which produced 300 clusters in 200 interactions. The convergence threshold, or minimum amount of pixels changed between interactions, was 0.95. The 300 clusters were compressed and regrouped into 20 classes that could be identified based upon visual interpretation in the area of study (Figure 4.3).

Using these twenty classes as training data, both MLC and SAM were conducted for the two sections. While MLC was conducted using ERDAS Image 9, SAM was performed using ENVI 4.3, similarly to South et al. (2004). Spectral endmembers of the twenty signatures were exported throughout a .txt extension to ENVI 4.3; a spectral angle mapper was conducted using a 10° angle.

After the maps containing the twenty classes were obtained with MLC and SAM, pixels of the final map images were re-assigned using the majority group of the neighborhood application of ERDAS (Lass et al. 2002; Okamoto et al. 2007). Using the model maker feature of ERDAS, the twenty classes were combined in five final

classification classes: Cut-leaved teasel, tree plus shrub, bare soil, water, and grass plus broadleaf. This process adopted the one reported in Carson et al. (1995) and Lass et al. (1999), who combined multiple targets into a single class during the classification of yellow starthistle.

Because hyperspectral images are relatively expensive and represent a large redundant data set, band reduction was performed to reduce processing time and storage requirements. Band reduction was conducted using Difference Ratio Ranking (DRR), which detects maximum absolute differences among classes by comparing the normalized difference between the target weed (cut-leaved teasel) and other targets (Zhou 2007).

Assessment of the accuracy of the classified map was performed by construction of the error matrix and calculation of the kappa statistic. Producer's and user's accuracy was calculated to compare reference data with classified data (Congalton and Green 1999; Jensen 2004; Lunetta and Lyon 2004). While the user's accuracy is calculated as a ratio of the correct point classified divided by the total reference point of this class, the producer's accuracy is calculate by dividing the correct number of pixels classified by the total number of pixels classified for that class (Congalton and Green 1999; Jensen 2004).

The Kappa statistic measured the agreement between the classified map and reference data (Jensen 2004):

$$K = \frac{N \sum x_{ii} - \sum (x_{i+} \times x_{+i})}{[N^2 - \sum (x_{i+} \times x_{+i})]}$$

Where N= the total number of data for the error matrix,

x_{ii} = diagonal values of the error matrix,

x_{i+} = the sum of samples in each row (row total),

X_{+j} = the sum of samples in each column (column total), and

$X_{i+} \times X_{+j}$ = multiplication of row 1 with column 1 in the error matrix

Reference data were collected throughout the field survey, including digital photo-interpretation of high resolution aerial photos taken in 2007, and original photo hyperpectral images. Fifty samples for each land-cover class were selected in stratified random sampling following the recommendation by Congalton and Green (1999) or Jensen (2004).

RESULTS AND DISCUSSION

Optimal bands were selected by comparing the maximum differences between the different targets and cut-leaved teasel. Figure 4.4 shows the value of difference ratios among the 63 bands for cut-leaved teasel and the grass plus broadleaf categories, which was a category that could be mistaken for teasel. Tree, water, and bare soil can be identified easily and were not shown. Large values for the difference ratios in band 30 and 31 were observed, but not for bands 16 to 18. Some bands had difference ratios lower than 0.3, which could lead to misclassification between cut-leaved teasel and grass plus broadleaf when bands were reduced. Also, there were no bands selected after 55. Based upon Figure 4.4, twelve spectral bands were selected at average wavelength of 401, 409, 454, 472, 666, 675, 732, 780, 789, 847, 885 and 904 nm, corresponding to band 1, 2, 7, 9, 30, 31, 37, 42, 43, 49, 53, and 55 of the original 63 bands.

Maximum Likelihood Classification

The MLC-classified maps at Exit 89 and Lamine sections were shown in Figure 4.5. Class maps from both the 63band and 12band AISA images were displayed. Most of the cut-leaved teasel patches were observed in the right-of-way area adjacent to the paved travel ways. In general, the 63band class map provided more information about the targets, yielding a higher accuracy than the 12band map. Table 4.1 demonstrates that the MLC approach reached an overall accuracy greater than 85%. Cut-leaved teasel from 63bands reached higher producer's and user's accuracies (>82%) than that from the 12band images at both study sites. The overall accuracy of class maps was 4 to 7% lower due to band reduction. For cut-leaved teasel, a large reduction of producer's accuracy (17 to 19% at two sites) could be observed. While user's accuracy at Exit 89 decreased 6%, the accuracy increased 3% at Lamine. Most of the classification errors (omission and commission) came from the confusion between grass plus broadleaf and cut-leaved teasel (Appendix A.1, A.2, A.5, A.6).

When the number of spectral bands was reduced, the overall kappa decreased 0.06 to 0.09 at Lamine and Exit 89, respectively (Table 4.3). The kappa for cut-leaved teasel decreased 0.07 to 0.02, which was lower than the reduction of overall kappa value.

Spectral angle mapper

After several determinations, a pre-defined reference angle of 10° was selected for the SAM classification in this study. The SAM-classified maps are shown in Figure 4.5 for the Exit 89 and Lamine sections. Map showed of distribution of each class and

additional unclassified pixels. Unclassified pixels reach up to 6.9% in Lamine section (Figure 4.5 c).

From Table 4.2 at both sites, the overall accuracy of the SAM approach was much lower (from 10 to 35%) than that of the MLC approach. Band selection did not affect the overall accuracy of SAM classification, since the kappa statistic was only reduced by 0.02 (Table 4.3). Producer's accuracy decreased 23 to 30% and user's accuracy decreased 14 to 27% at both sites. The conditional kappa statistic was reduced as much as 0.18 to 0.34 (Table 4.3), which was significantly more compared to the MLC approach. Errors of commission resulted in improper classification of cut-leaved teasel for 10 pixels at Exit 89 and 6 pixels at Lamine when working with 63 band images (Appendix A.3, A.7). Improper classification of teasel occurred for 10 and 5 pixels at Exit 89 and Lamine, respectively, using twelve band images (Appendix A.4, A.8).

Results in this study demonstrate that the probability-based MLC attained a greater level of accuracy compared to the SAM classifier in detecting cut-leaved teasel patches. This agrees with Shafri et al. (2007), who mapped seven different tree classes in a mixed forest using 20 band hyperspectral images. Shafri et al. (2007) reported that the maximum overall accuracy was 85% with MLC compared to only 48.8% with SAM. The kappa statistic values in both studies were also smaller with SAM compared to MLC. Although SAM has been proven an effective approach in land cover mapping with hyperspectral images, little is known on the utility of SAM in heterogeneous environments such as roadsides. In this situation, pixels are comprised of a mixture of one or more land cover types. For example, cut-leaved teasel along highways often grew in narrow, long patches. The spectral response of pixels from these patches was often a

combination of cut-leaved teasel and grass plus broadleaf species. With that combination of species, the probability-based MLC may be more suitable to map the distribution of cut-leaved teasel patches along highways.

Although spectral band reduction has been approved as a useful method for reducing storage space for data and the computation time of hyperspectral images, this reduction was not effective in mixed environments. In comparing classification results with AISA images for 12 versus 63 bands, the accuracy of detecting cut-leaved teasel was reduced using both MLC and SAM methods. The accuracy of SAM with the 12 bands was very low and thus unacceptable in practical applications.

In site-specific weed management, it is critical to detect locations of invasive weeds prior to treatment. In this study hyperspectral images could detect cut-leaved teasel with moderately high accuracy (>80%) and a large conditional Kappa statistic (0.8) at two sites. The approaches developed in this study could also be adopted to detect other invasive species in Missouri.

LITERATURE CITED

- Aspinall, R. 2002. A geographic information science perspective on hyperspectral remote sensing. *Journal of Geographic System* 4:127-140.
- Bentivegna, D.J. 2006. Biology and management of cut-leaved teasel (*Dipsacus laciniatus* L.) in Central Missouri. MS. University of Missouri. 67 p.
- Campbell, J.B. 2002. Introduction to Remote Sensing. The Guilford Press, New York, NY. 620 p.
- Carson, H. W., L. W. Lass, and R. H. Callihan 1995. Detection of yellow hawkweed (*Hieracium pretense*) with high resolution multispectral digital imagery. *Weed Technology* 9:477-483.
- Congalton, R.G. and K. Green. 1999. Assessing the accuracy of remotely sensed data: principles and practices. CRC Press, Boca Raton, FL. 137 p.
- ENVI. 2006. The environment for visualizing images. ENVI Tutorials, version 4.3. Research System Institute, USA.
- ERDAS Image. 2005. ERDAS Field Guide™. Version :ERDAS 9. Leica Geosystems Geospatial Imaging, LLC. 705 p.
- Jensen, J.R. 2004. Thematic map accuracy assessment. *in*: Introductory digital image processing. Printice Hall, Upper Saddle River, NJ. Pp. 495-515.
- Lass, L.W., H.W. Carson, and R.H. Calliham. 1996. Detection of yellow starthistle (*Centaurea solstitialis*) and common St. Johnswort (*Hypericum perforatum*) with multispectral digital imagery. *Weed Technology* 10:466-474.

- Lass, L.W., D.C. Thill, B. Shaffii, and T.S. Prather. 2002. Detecting spotted knapweed (*Centaurea maculosa*) with hyperspectral remote sensing technology. *Weed Technology* 16:426-432.
- Lawrence, R. L., S.D. Wood , and R.L. Sheley. 2006. Mapping invasive plants using hyperspectral imagery and Breiman Cutler classifications (RandomForest). *Remote Sensing of Environment* 100:356-362.
- Lunetta, R.S. and J.G. Lyon. 2004. Remote sensing and GIS accuracy assessment. CRC Press, Boca Raton, FL. 304 p.
- Medlin, C. R., D. R. Shaw, P. D. Gerard, and F.E. LaMastus. 2000. Using remote sensing to detect weed infestation in *Glycine max*. *Weed Science* 48:393-398.
- National Resources Conservation Service. 2008. <http://soils.usda.gov/> access May 2008.
- Nagendra, H. 2001. Using remote sensing to assess biodiversity. *International Journal of Remote Sensing* 22:2,377-2,400.
- Schowengerdt, R.A. 2007. Remote Sensing. Model and methods for image processing. Elsevier Press. London, UK. 516 p
- Shafri, H.Z.M., A.Suhaili, and S.Mansor. 2007. The performance of maximum likelihood, spectral angle mapper, neural network and decision tree classification in hyperspectral image analysis. *Journal of Computer Science* 3:419-423.
- Shaw, D.R.. 2005. Translation of remote sensing data into weed management decisions .*Weed Science* 53:264-273.
- Solecki, M.K. 1993. Cut-leaved and common teasel (*Dipsacus laciniatus* L. and *D. Sylvestris* Huds.): Profile of two invasive aliens. *in*: McKnight, B.N. ed.,

- Biological Pollution: The control and Impact of Invasive Exotic species. Indiana Academy of Science, Indianapolis, IN. Pp. 85-92.
- South, S., J. Qi, and D.P. Lusch. 2004. Optimal classification methods for mapping agricultural tillage practices. *Remote Sensing of Environment* 91:90-97.
- Tsai, F., E. K. Lin, and K.Yoshino. 2007. Spectrally segmented principal component analysis of hyperspectral imagery for mapping invasive plant species. *International Journal of Remote Sensing* 28:1,023-1,039.
- Underwood, E., S. Ustin and D. DiPietro. 2003. Mapping non-native plants using hyperspectral imagery. *Remote Sensing of Environment* 86:150-161.
- USDA. 2008. The PLANTS Database, Version 3.5 (<http://plants.usda.gov>). National Plant Data Center, Baton Rouge, LA 70874-4490 USA. Accessed May 20, 2008.
- Ustin, S.L., D.A. Roberts, J.A. Gamon, G.P.Asner, and R.O. Green. 2004. Using imaging spectroscopy to study ecosystem processes and properties. *BioScience* 54:523-534.
- Wang, C., B. Zhou, and H. L. Palm. 2008. Detecting invasive *Sericia lespedeza* (*Lespedeza cuneata*) in mid-Missouri pastureland using hyperspectral imagery. *Environmental Management* 41:853-862.
- Werner, P.A. 1975a. The biology of Canadian weeds 12. *Dipsacus sylvestris* Huds. *Canadian Journal Plant Science* 55:783-794.
- Werner, P.A. 1975b. A seed trap for determining patterns of seed deposition in terrestrial plants. *Canadian Journal of Botany* 53:810-813.
- Zhou, B. 2007. Application of hyperspectral remote sensing in detecting and mapping *Sericia lespedeza* in Missouri. M.S. thesis University of Missouri. 81 p.

Table 4.1. Producer's and user's accuracy of the classification of hyperspectral image (63 and 12 bands) for Exit 89 (A) and Lamine (B) I-70 highway sections using Maximum Likelihood classification methodology on July 2006.

A)	63 bands		12 bands	
	Producer	User	Producer	User
	Accuracy	Accuracy	Accuracy	Accuracy
Cut-leaved teasel	89.1	82	69.6	76.2
Water	100	100	94	100
Bare Soil	90.2	92	92.2	81
Tree+shrub	100	94	95.74	90
Grass+broadleaf	83.93	94	76.8	81
Overall Classification	92.4 %		85.6 %	

B)	63 bands		12 bands	
	Producer	User	Producer	User
	Accuracy	Accuracy	Accuracy	Accuracy
Cut-leaved teasel	89.4	84	72.3	87.2
Water	100	90	97.8	91.7
Bare Soil	95.9	94	93.9	88.5
Tree+shrub	87.5	98	83.9	95.6
Grass+broadleaf	79.3	84	83	71
Overall Classification	90 %		86 %	

Table 4.2. Producer's and user's accuracy of the classification of hyperspectral images (63 and 12 bands) for Exit 89 (A) and Lamine (B) I-70 highway sections using spectral angle mapper of 10° as a classification methodology in July 2006.

A)	63 bands		12 bands	
	Producer	User	Producer	User
	Accuracy	Accuracy	Accuracy	Accuracy
Cut-leaved teasel	63	74	32.6	60
Water	76	100	80	100
Bare Soil	78.4	89.9	84.31	89.6
Tree +shrub	89.4	93.3	87.2	95.4
Grass+broadleaf	76.8	68.3	87.5	55.7
Overall Classification	76.8%		75.2%	

B)	63 bands		12 bands	
	Producer	User	Producer	User
	Accuracy	Accuracy	Accuracy	Accuracy
Cut-leaved teasel	36.2	77.3	12.8	50
Water	6.52	100	39.1	85.7
Bare Soil	58.33	100	62.5	88.2
Tree+shrub	85.5	53.2	83.6	71.9
Grass+broadleaf	77.8	53.2	68.5	37.4
Overall Classification	54.8 %		54.8 %	

Table 4.3. Kappa statistic of the classification hyperspectral (63 and 12 bands) images on Exit 89 and Lamine highway sections using maximum likelihood (A) and spectral angle mapper of 10° (B) as classification methodologies in July, 2006.

A) Maximum likelihood				
Target	Exit		Lamine	
	63 bands	12 bands	63 bands	12 bands
Cut-leaved teasel	0.78	0.71	0.80	0.78
Water	1	1	0.88	0.84
Bare Soil	0.90	0.76	0.93	0.60
Tree+shrub	0.93	0.88	0.97	0.95
Grass+broadleaf	0.92	0.76	0.80	0.63
Overall Kappa	0.91	0.82	0.88	0.82

B) Spectral angle mapper				
Target	Exit		Lamine	
	63 bands	12 bands	63 bands	12 bands
Cut-leaved teasel	0.69	0.51	0.72	0.38
Water	1	1	1	0.82
Bare Soil	0.86	0.87	1	0.85
Tree+shrub	0.92	0.94	0.81	0.64
Grass+broadleaf	0.59	0.43	0.42	0.20
Overall Kappa	0.71	0.69	0.46	0.44



Figure 4.1. Patches of cut-leaved teasel along Interstate Highway I-70 between mile markers 89-93 in central Missouri. Photo was taken September 27, 2006.

A)



B)

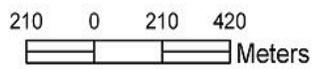


Figure 4.2. Hyperspectral images composed of Red-Green-Blue bands from Interstate Highway I-70 in Copper County, MO. Images were recorded for Exit 89 A) and Lamine B).

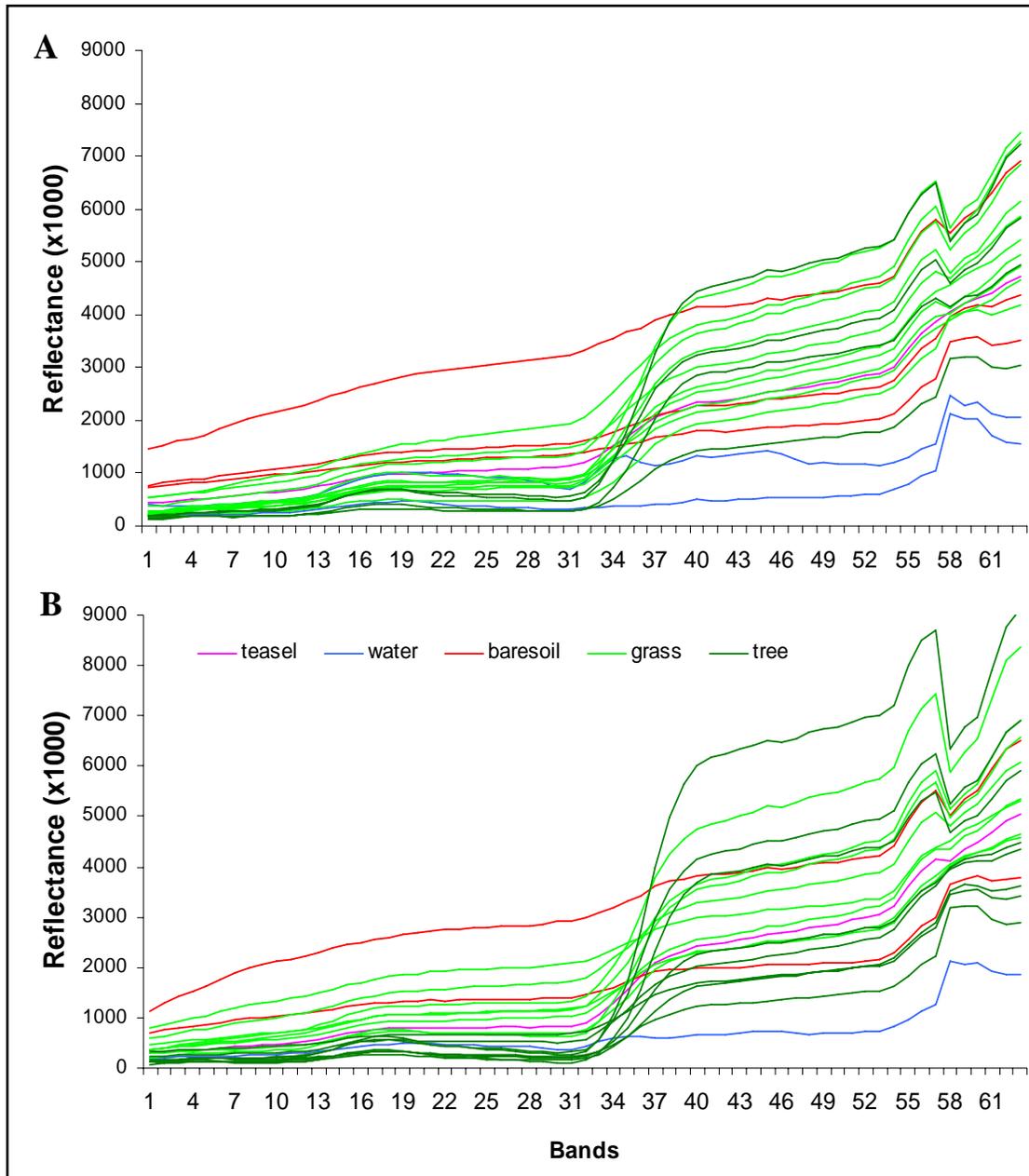


Figure 4.3. Spectral signature of the twenty targets recorded on July 25, 2006 in Cooper County, MO with hyperspectral sensors. Targets were recorded for Exit 89 (A) and Lamine (B).

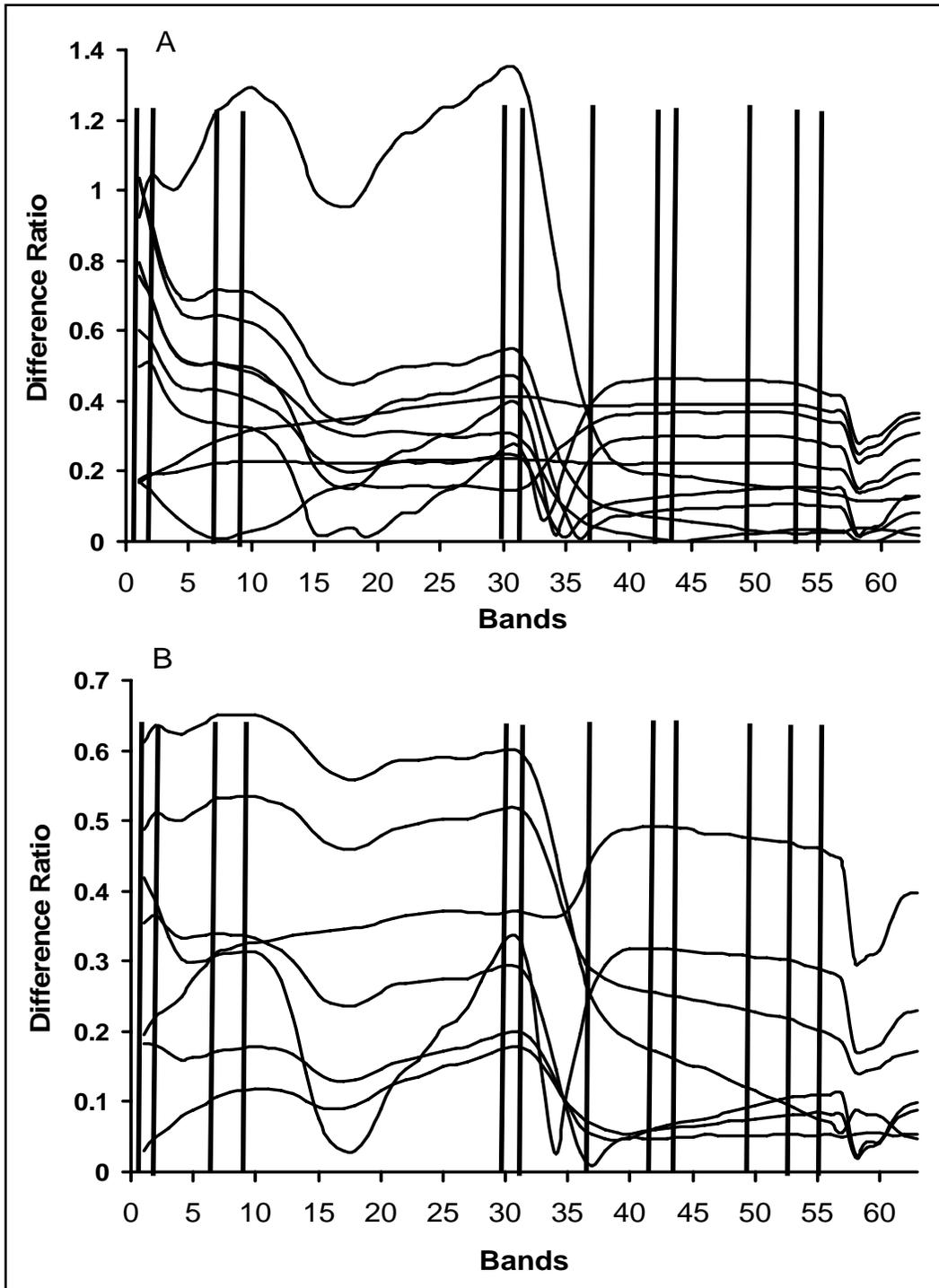


Figure 4.4. Difference ratio ranking for cut-leaved teasel and grasses spectral reflectance and selected bands in Exit 89 (A) and Lamine (B) recorded with hyperspectral sensor on July 25, 2006 in Cooper County, MO.

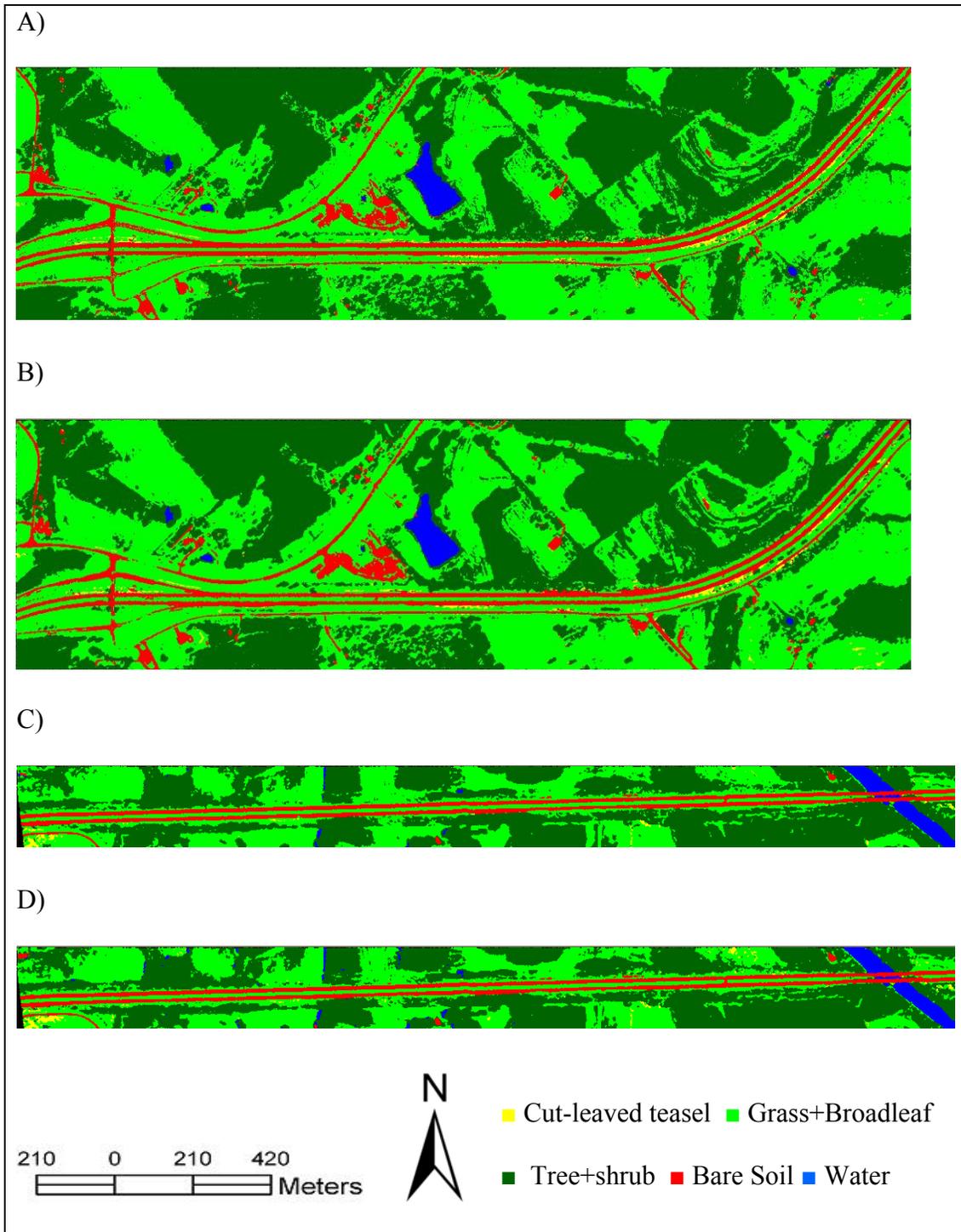


Figure 4.5. Classification map of various targets generated in July, 2006 using maximum likelihood classifier for two sites in Cooper County, MO. These sites included Exit 89 (A, B) and Lamine (C, D) sections of Highway I-70 with hyperspectral images 63 bands (A, C) and 12 bands (B, D).

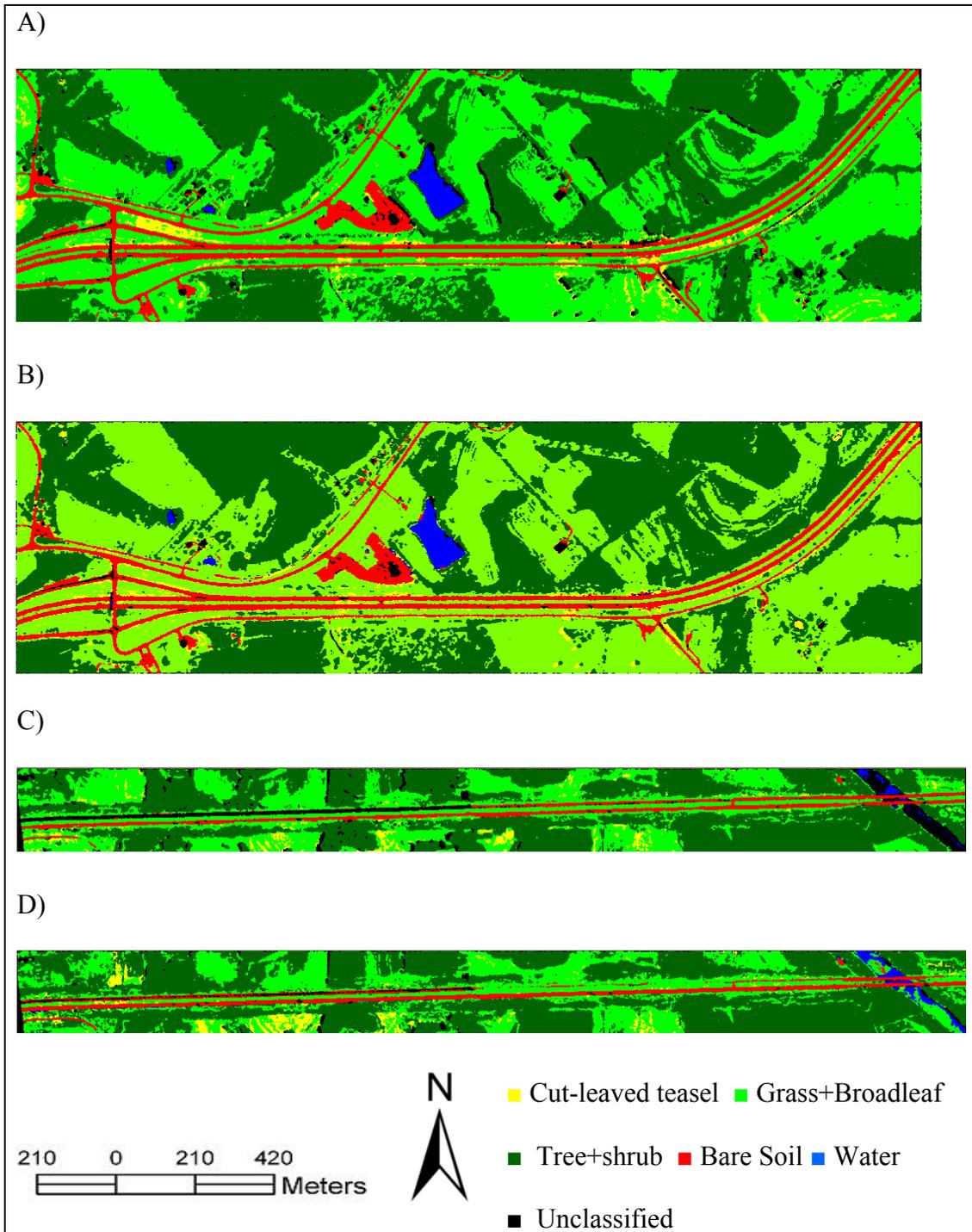


Figure 4.6. Classification map generating various targets in July, 2006 using spectral angle mapper (10° angle) classifier for two sites in Cooper County, MO. These sites included Exit 89 (A, B) and Lamine (C, D) sections of Interstate Highway I-70 with hyperspectral images 63 bands (A, C) and 12 bands (B, D).

CHAPTER V

Cut-leaved teasel (*Dipsacus laciniatus* L.) control along roadsides in Missouri

Abstract: Cut-leaved teasel is an invasive weed in Missouri that thrives along roadsides. Effective, long-term management requires control of existing plants and establishment of desirable vegetation to preclude re-infestations. Cut-leaved teasel rosettes along Interstate Highway 70 (mile marker 89 to 93) in Cooper County were treated with a combination of herbicides and then seeded with grasses. Four herbicides were applied to teasel infested areas in fall 2006 and spring 2007: Dicamba plus diflufenzopyr, aminopyralid, triclopyr, and metsulfuron-methyl. Each treated plot was divided in half, and overseeded with buffalograss combined with tall fescue or Canada wildrye. Aminopyralid resulted in greater than 95% cut-leaved teasel control, and control remained >90% up to 6 months later. In aminopyralid plots, soil coverage by seeded grasses reached up to 97%. Triclopyr control of cut-leaved teasel was unacceptable (<50%), with only 39% of the treated area covered by seeded grasses. Suppression of cut-leaved teasel by metsulfuron-methyl reached 88%. Control of teasel was the primary factor responsible for successful grass establishment.

Nomenclature: invasive, herbicide, roadside, DIWLA¹.

Additional Index Words: herbicide, grass seeding, .

¹ USA code for *Dipsacus Laciniatus* L. in WSSA-approved *Composite List of Weeds*. Revised 2008. WSSA 810 East 10th street, Lawrence, KS 66044-8897.

INTRODUCTION

Cut-leaved teasel is categorized as an invasive, noxious weed in Missouri. In New York around 1840, teasel was introduced from France for the textile industry to align wool fiber (Terres and Ratcliffe 1979). Upon mechanization of spinning wool, teasel was abandoned as a crop and began to spread. Solecki (1993) claimed that the spread of teasel has been facilitated by the construction of the interstate highway system. Solecki (1993) showed the initial population of cut-leaved teasel in Missouri occurred in Kansas City in 1980. Yatskievych (2006) documented a population in Harrison County in 1968. Today, Cut-leaved teasel is found in many counties, particularly along the median of Interstate 70 and Highway 63.

Cut-leaved teasel is a biennial that grows initially as a rosette and reaches two meters in height during reproduction the second year (Werner 1975b). Leaves are oblong-lanceolate with irregular serrations (Yatskievych 2006). Bentivegna (2006) documented that a dense concentration of leaves resulted in a high leaf area index (>3), that allows plants to crowd out other species (Werner 1975a). In the *Dipsacus* genus, cut-leaved teasel is reportedly the most aggressive species (Solecki 1993). Plants can produce up to 33,500 seeds per plant (Bentivegna 2006), and emerges in both fall and spring. Seed persists in the soil up to 5 years (Robert 1986). Seed dispersal is around the parent plant, which results in compact patches of teasel (Werner 1975a).

Management of cut-leaved teasel involves strategies aimed to reduce the number of rosettes and prevent seed production. Cut-leaved teasel control measures often involve mowing or application of herbicides (Glass 1991). Because teasel has a deep taproot,

multiple mowings of rosettes is necessary to control plant. If plants are only mowed once in June, regrowth occurs and plants produce viable seed (Cheesman 1998; Solecki 1993). Plants mowed in late summer (August) contain viable seed, which are then spread over a wider area. Postemergence herbicides are often effective for control of teasel. Labeled herbicides include: Growth regulators (aminopyralid, dicamba, triclopyr plus clopyralid) and acetolactate synthase inhibiting herbicides (metsulfuron-methyl) (Crop Protection Reference 2006).

Control measures remove cut-leaved teasel from treated areas, however the lack of other species and germination of new seedlings results in re-infestation. of cut-leaved teasel (Werner 1977). Because teasel excludes other species, control of populations also leads to soil erosion. Establishment of desirable plants after herbicide application can improve the reduction of weeds and can preclude re-infestation (Jacobs et al. 1999; O'Donnel and Adkins 2005). Teasel seedlings are sensitive to competition for light, and establishment of grasses can reduce teasel emergence (Werner 1975c, Werner 1977). Use of both cool season grasses such as tall fescue and Canada wildrye as well as warm season grasses (buffalograss) may result in a continuous barrier. Jacobs et al. (1999) described that the continuous use of resources for plant growth by desirable plants can reduce infestation by undesirable species.

Cut-leaved teasel was declared noxious in Missouri in 2000, requiring infested areas to be treated. The Missouri Department of Transportation (MoDOT) indicates that a significant area along roadsides is infested with teasel (Rand Swanigan, personal communication)². Currently, MoDOT uses a combination of mowing and herbicides to

² Rand Swanigan. Head of Roadside Management and Maintenance for MoDOT.

control teasel. However, control is often not possible along steep slopes and rocky outcrops

The integration of effective herbicides and establishment of competitive and adapted beneficial species can lead to effective management of cut-leaved teasel. The objective of this research was to identify an effective management program to remove teasel from established areas in Missouri.

MATERIALS AND METHODS

Teasel rosette control

Twenty plots, with an average of 200 m² and containing greater than 50% of the area with cut-leaved teasel, were selected between mile markers 89 to 93 along Interstate Highway 70 in central Missouri (Figure 5.1). Plots were cut mechanically in fall 2006 to remove dead vegetation. Four different herbicide programs were applied on November 3, 2006 and May 31, 2007. Herbicides were applied with a CO₂-pressurized backpack sprayer equipped with XR 8001 VS Teejet nozzles³, calibrated to deliver a carrier (water) volume of 147 L ha⁻¹, with an application velocity of 2.4 km hr⁻¹. Application dates and weather conditions at application were recorded. The herbicide programs and application times are listed in Table 5.1. Visual evaluation of herbicide effectiveness was recorded six times after treatment. The rating days were: November 21, 2006; March 20, 2007; May 31, 2007; June 14, 2007; July 3, 2007, and November 1, 2007. A scale of 0 to 100

³ TeeJet XR Spraying Systems CO., North Ave., Wheaton, IL 60188.

was used, where 0 indicated no visible effect and 100 indicated plant death. The herbicides were sprayed in randomized completed design with four replications.

Digital pictures were taken of each plot as another method of assessing teasel management (Figure 5.2). Six pictures were taken in each half of the plot to enable assessment of grass establishment in each plot. From each photo, visualization was possible using ENVI 4.3⁴ to identify four classes of interest: teasel, grass, bare soil, and other broadleaf species. The number of pixels was recorded and the percentage of cover was determined for each individual picture.

Grass establishment

Tall fescue (*Festuca arundinacea* Schreb.), Canada wildrye (*Elymus Canadensis* L.) and buffalograss (*Buchloe dactyloides* Nutt.) were established with a hand seeder. Tall fescue and Canada wildrye are cool-season grasses with optimal growth in spring and fall. In contrast, buffalograss is a warm-season grass that grows primarily in summer. Tall fescue and Canada wildrye were spread over half of each plot on November 8, 2006 and May 10, 2007, with buffalograss spread over the entire plot on May 10, 2007. Seeding rates were: 9.8 g.m⁻² for tall fescue, 4.4 g.m⁻² for Canada wildrye, and 3 g.m⁻² for buffalograss. Seed germination rates were 85, 80, and 80% for tall fescue, Canada wildrye and buffaboggrass, respectively.

Seedling teasel re-infestation

In November 2007, one year after management of cut-leaved teasel was initiated, emerged seedlings of cut-leaved teasel were counted in eight, one meter square areas

⁴ ENVI. ITT Industries, Inc. 4990 Pearl East Circle Boulder. CO 80301, USA.

within each plot. Plants in the cotyledon to six true leaves growth stage were considered seedlings.

All data were subjected to analysis of variance using SAS statistical software (SAS 2003). Test for Normality of Shapiro Wilk and analysis of residual for equal variance were conducted with PROC UNIVARIATE of SAS with a probability ≤ 0.05 . Teasel emergence data were transformed logarithmically prior to analysis to improve treatment separation. Means of significant main effects were separated using Fisher's Protected LSD at $p \leq 0.05$ (SAS 2003).

RESULTS AND DISCUSSION

Fifteen days after fall herbicide applications, cut-leaved teasel control ranged from 30 (triclopyr) to 45% (dicamba) (Figure 5.3). The level of control increased from 68 (triclopyr) to 98% (aminopyralid) in March 2007. By July 2007, four of the five herbicide programs resulted in 99% control. However, two applications of triclopyr resulted in only 38% control (Figure 5.3). It is apparent that a number of herbicides are effective for control of cut-leaved teasel, but more than one application in a twelve month period is needed (Werner 1975b)

Grass establishment was monitored in July and November 2007 to determine any impact from the herbicides applied. There was no three way interaction among evaluation time (July-November), grasses (Canada wildrye-tall fescue), and the five herbicide programs. Coverage by Canada wildrye ranged from 65 to 84.8% for the five herbicide programs in July 2007, and decreased to 47.5 to 71.3% by November (Table 5.3). For

tall fescue, coverage ranged from 66.3 to 84.8% for the five herbicide programs in July 2007, and decreased to 45 to 71.8% by November. Establishment of Canada wildrye and tall fescue was lowest in November for the triclopyr treatment, which was consistent with poor teasel control. Mean establishment of Canada wildrye and tall fescue was greatest for the aminopyralid treatment. This reflects the efficacy of aminopyralid on teasel, and little impact on grasses.

Emergence of cut-leaved teasel seedlings in November 2007 was reduced 72 to 92% for aminopyralid compared to triclopyr (Table 5.2). Aminopyralid was the only herbicide program to significantly reduce teasel seedling populations by November, but emergence in the triclopyr treated areas was numerically highest in both the Canada wildrye and tall fescue plots.

The presence of grasses reduced new infestations of cut-leaved teasel. Werner (1977) showed that dense stands of grasses reduced seedling emergence. In comparison, seedling emergence of musk thistle (*Carduus nutans*), a biennial plant with a large taproot, was also reduced by the presence of grasses (Wardle et al. 1995). Tall fescue as well as other grasses along highway right-of-ways enhances the overall appearance (Bennett 1979)

Digital pictures taken in November revealed that grasses and cut-leaved teasel comprised more than 70% of the area in each plot, with bare ground and the presence of other species representing the remainder of the area. (Figure 5.4). Plots treated with metsulfuron-methyl, dicamba, or aminopyralid contained from 65 to 95% grass, with grass cover the highest for aminopyralid treated areas. The amount of area covered by cut-leaved teasel was less than 5%. Grass coverage in triclopyr treated plots was only

39%, while cut-leaved teasel represented 37% of the area (Figure 5.4). Plots treated with metsulfuron-methyl or dicamba contained from 5 to 25% coverage with other species: common milkweed (*Asclepias syriaca*), common ragweed (*Ambrosia artemisiifolia*), horsenettle (*Solanum carolinense*), and sericea lespedeza (*Lespedeza cuneata*). The use of metsulfuron-methyl or dicamba resulted in less control of other species compared to aminopyralid, which resulted in 15 to 30% less grass cover. Digital pictures provided an effective method to assess vegetation control and grass establishment compared with the visual evaluations.

In conclusion, repeated application of aminopyralid resulted in greater than 95% control of teasel, and also provided excellent control of other undesirable species. The activity of aminopyralid did not impact the establishment of Canada wildrye and tall fescue, with grass coverage exceeding 95%. Teasel control with metsulfuron-methyl and dicamba exceeded 90%, but control of other undesirable species was less effective, resulting in 5-25% of the area covered by these species. As a result, grass establishment was 15 to 30% lower compared to aminopyralid. Triclopyr was not effective in managing cut-leaved teasel, with 37% of the plot area covered by plants at the end of the study. Control of other undesirable species was also unacceptable with triclopyr, with 20% of the area dominated by these species. Grass establishment was lowest (39% of the plot area) with triclopyr and reflected strong competition from cut-leaved teasel and other undesirable species. Robert (1986) reported that eradication of cut-leaved teasel from infested sites is a long-term (greater than 5 years) process; the combination of herbicides and established grasses provides a sound approach for reducing infestations of cut-leaved teasel

LITERATURE CITED

- Bentivegna, D.J. 2006. Biology and management of cut-leaved teasel (*Dipsacus laciniatus* L.) in Central Missouri. M.S. University of Missouri. 67 p.
- Bennett, O.L. 1979. Conservation. *in*: Tall Fescue. Ed. Buckner R.C. and L.P.Bush. Pp 319-340.
- Cheesman, O.D. 1998. The impact of some field boundary management practices on the development of *Dipsacus fullonum* L. flowering stems, and implication for conservation. *Agriculture, Ecosystems and Environment* 68:41-49.
- Crop Protection Reference. 2006. C & O press. 302 5th Avenue New York, NT. 2,395 p.
- Glass, W.D. 1991. Vegetation management guideline: cut-leaved teasel (*Dipsacus laciniatus* L.) and common teasel (*Dipsacus sylvestris* Huds.). *Natural Areas Journal* 11:213-214.
- Jacobs, J.S., M.F. Carpinelli, and R.L. Sheley. 1999. Revegetating noxious weed-infested rangeland. *in*: Biology and management off noxious rangeland weeds ed. R.L Shelley and J.K. Petroff. Oregon State University Press, Corvallis, OR. Pp 133-141.
- Robert, H.A. 1986. Seed persistence in soil and seasonal emergence in plant species from different habitats. *Journal of Applied Ecology* 23:639-656.
- SAS. 2003. Statistical Analysis Systme. SAS/STAT User's Guide. Release 9.1. Software version 8e. Cary, NC:Statistical Analysis Systems Institute.
- Solecki, M.K. 1993. Cut-leaved and common Teasel (*Dipsacus laciniatus* L. and *D. Sylvestris* Huds.): profile of two invasive aliens. *in*: McKnight, B.N. ed. Biological Pollution: The control and Impact of Invasive Exotic species. Indiana Academy of Science, Indianapolis, IN. Pp 85-92.

- O'Donnell, C. and S.W. Adkins. 2005. Management of parthenium weed through competitive displacement with beneficial plants. *Weed Biology and Management* 5:77-79.
- SAS. 2003. Statistical Analysis System. SAS/STAT User's Guide. Release 9.1. Software version 8e. Cary, NC:Statistical Analysis Systems Institute.
- Terres, J. K. and B. Ratcliffe. 1979. Teasel, as in Tease. *Audubon*. 9:108-109.
- Warfle, D.A., K.S. Nicholson, M. Ahmed, and A. Rahman. 1995. Influence of pasture forage species on seedling emergence, growth and development of *Carduus nutans*. *Journal of Applied Ecology* 32:225-233.
- Werner, P.A. 1975a. A seed trap for determining patterns of seed deposition in terrestrial plant. *Canadian Journal of Botany* 53:810-813.
- Werner, P.A. 1975b. The biology of Canadian weeds 12. *Dipsacus sylvestris* Huds. *Canadian Journal Plant Science* 55:783-794.
- Werner, P.A. 1975c. The effect of plant litter on germination in teasel, *Dipsacus sylvestris* Huds. *The American Midland Naturalist* 94:470-476.
- Werner, P.A. 1977. Colonization success of a "biennial" plant species: experiment field studies of species cohabitation and replacement. *Ecology* 58:840-849.
- Yatskievych, G. 2006. Dipsacaceae. in Steyermark's Flora of Missouri. 2:988-990.

Table 5.1. Herbicide programs and application timings for cut-leaved teasel (*Dipsacus laciniatus* L.) control along Interstate Highway 70 from mile markers 89 to 93 in Cooper County, Missouri.

Herbicide	Active ingredient	Time	Rate	Adjuvant (% v/v)
Escort	Metsulfuron-methyl	Fall 2006	0.0175 kg ha ⁻¹	NIS 0.5%
Escort	Metsulfuron-methyl	Spring 2007	0.0175 kg ha ⁻¹	NIS 0.5 %
Milestone	Aminopyralid	Fall 2006	0.42 kg ha ⁻¹	NIS 0.5 %
Milestone	Aminopyralid	Spring 2007	0.42 kg ha ⁻¹	NIS 0.5 %
Garlon 3A	Triclopyr	Fall 2006	3.36 kg ha ⁻¹	NIS 0.5 %
Garlon 3A	Triclopyr	Spring 2007	3.36 kg ha ⁻¹	NIS 0.5 %
Distinct	Dicamba + Diflufenzopyr	Fall 2006	0.42 kg ha ⁻¹	NIS 0.25 % +UAN 1.25%
Distinct	Dicamba + Diflufenzopyr	Spring 2007	0.42 kg ha ⁻¹	NIS 0.25 % +UAN 1.25%
Escort	Metsulfuron-methyl	Fall 2006	0.0175 kg ha ⁻¹	NIS 0.5%
Distinct	Dicamba + Diflufenzopyr	Spring 2007	0.42 kg ha ⁻¹	NIS 0.25 % +UAN 1.25%

NIS: Non-ionic surfactant

UAN: Urea-Ammonium nitrate

Table 5.2. Means grass establishment and cut-leaved teasel density for the integrated herbicide/grass seeding program. Treatments were established in Cooper County, Missouri along Interstate highway 70 from mile marker 89 to 93.

Herbicides		Grass Type	Grass Establishment		Teasel seedlings
Fall 2006	Spring 2007		(% cover) ^a		(No. per m ²) ^b
			July 2007	November 2007	November 2007
Triclopyr	Triclopyr	Canada wildrye	67.5±6.5	47.5±26.3	36.6 A
Metsulfuron-methyl	Dicamba	Canada wildrye	84.8±12.5	58.8±21.4	29.9 A
Dicamba	Dicamba	Canada wildrye	78.8±6.3	66.3±19.3	17 A
Metsulfuron-methyl	Metsulfuron-methyl	Canada wildrye	65 ± 23.4	66.3±11.8	15.3 A
Aminopyralid	Aminopyralid	Canada wildrye	79.5±26.4	71.3±22.5	10.3 B
Triclopyr	Triclopyr	Tall Fescue	66.3±14.9	45±28.6	29.7A
Metsulfuron-methyl	Dicamba	Tall Fescue	84.8±12.5	58.8±21.4	25.3 A
Dicamba	Dicamba	Tall Fescue	70±6.8	70±15.8	18.3 A
Metsulfuron-methyl	Metsulfuron-methyl	Tall Fescue	67.5±14.3	60±17.7	27.3 A
Aminopyralid	Aminopyralid	Tall Fescue	80.8±21	73.8±18.9	2.4 B

^a The standard deviation for grass establishment follows the estimated mean.

^b Means followed by the same letter in each column are not significantly different according to Fisher Protected LSD at $p \leq 0.05$.



Figure 5.1. Distribution of the plots along Highway I-70 (marker 89-93), Cooper County, MO. Red square showed the location of each plot.



Figure 5.2. A representative digital picture taken during plot evaluation in November 2007.

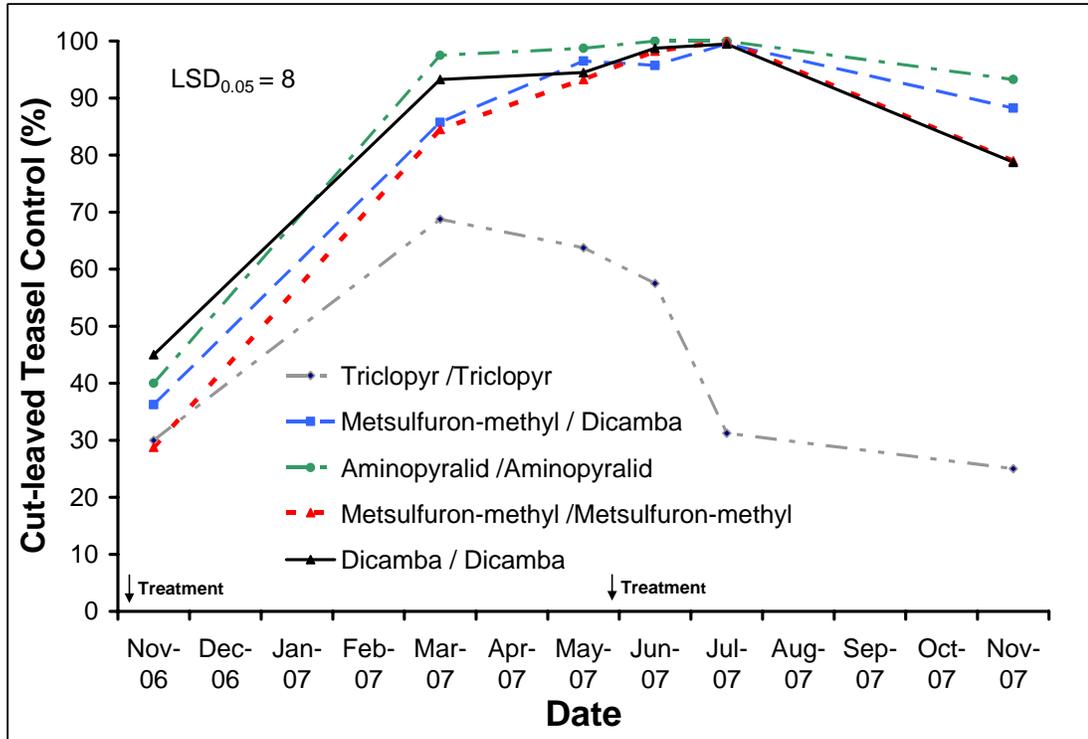


Figure 5.3. Effect of fall and spring applied herbicides on cut-leaved teasel (*Dipsacus laciniatus*L.) along Interstate highway 70 from mile marker 89 to 93, Cooper County, MO. Mean separation for each herbicide and evaluation date was possible using Fisher’s protected LSD at $p \leq 0.05$.

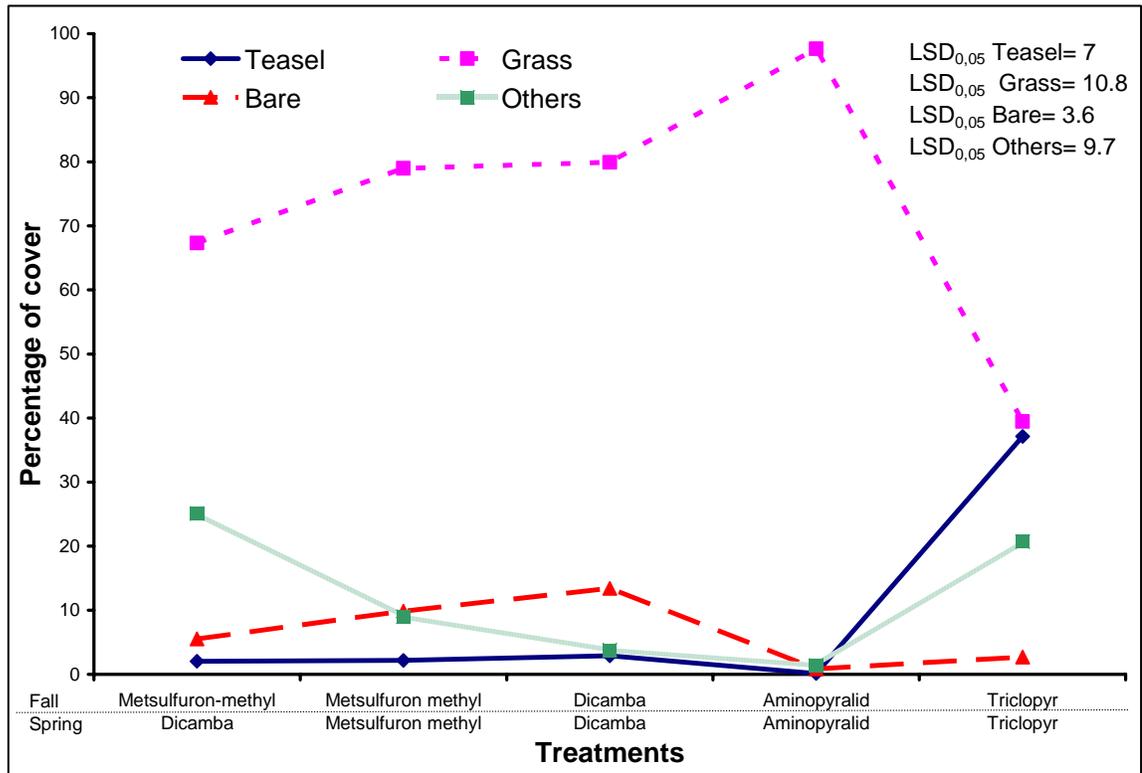


Figure 5.4. Evaluation of grass establishment along Interstate Highway 70 from mile marker 89 to 93 in November 2007. Numerical estimates of grass coverage were determined by analysis of digital pictures using ENVI software. The total coverage of a given area is 100% and corresponds to the sum of the four categories. Means for each category of soil coverage were evaluated by Fisher's Protected LSD at $p \leq 0.05$.

CHAPTER VI

Integrated Management of Cut-leaved Teasel (*Dipsacus laciniatus* L.) in Missouri

Cut-leaved leaved teasel is rapidly spreading along roadsides across the US. Introduced to the US from France in 1840, plants were important in the alignment of wool fiber prior to spinning (Terres and Ratcliffe 1979). Once mechanization was developed, cut-leaved teasel plants were discarded as a weed and spread from the East to the West. Declared noxious in Missouri in 2000, cut-leaved teasel decreases the diversification of native species due to strong competition. In addition, flowering plants reduce traffic visibility, which can increase the hazards to motorists.

Management of cut-leaved teasel is poorly understood, and there is little knowledge on the biology of plants. Overlapping knowledge on the biology of plants and their response to herbicides will allow implementation of management strategies. Cut-leaved teasel management is based upon three pillars (Figure 6.1). Knowledge regarding each pillar will answer several key questions necessary for optimum, sustainable management

- * Biology: Why is cut-leaved teasel so successful? What is the vulnerable part of the plants life cycle? How does teasel grow under natural conditions?

- * Detection: How can teasel be differentiated from other species using remote sensing?

- * Management: Can herbicide use be combined with establishment of desirable species to reduce infestations of teasel?

Biology

Cut-leaved teasel is a biennial plant that establishes a strong rosette during the first year and bolts in early spring the second year (Solecki 1993; Werner 1975b). Figure 6.2 shows the life cycle of cut-leaved teasel. Knowledge regarding the biology of plants may indicate a weak part of the plants life cycle. Of interest is the type and extent of biology information necessary for optimum management. Concern involves what kind of information about biology as well as how much biology information it needs to do optimum management. In general, in the first two steps in the invasion process: arrival and establishment (Figure 6.3), it is possible to eradicate cut-leaved teasel with little or superficial knowledge of the plant biology (Simberloff 2003). On the other hand, in the last two steps; spread and range expansion (Figure 6.3), it is impossible to have effective control without knowledge of important plant growth characteristics. In general, intensive population research by itself no guarantees a solution to the invasive plant infestation (Simberloff 2003)

Seeds are an important part of the life cycle of cut-leaved teasel, because this is a key to range expansion. Biennial plants like cut-leaved teasel are limited in population growth in 80% due seed presence (Myers and Bazely 2003). Cut-leaved teasel plants produced up to 10,400 seeds when growing in close proximity to other teasel plants, and 33,500 seeds when plants grew 30 cm from other teasel plants. This would suggest that plants arriving at a new site increase their chance for survival by increasing seed production (Bentivegna 2006). Seedling emergence patterns, seed maturation, and seed persistence (Chapter 2) were studied to understand the periodicity of plant establishment

and the longevity of cut-leaved teasel once seed are produced.. For example, herbicidal control after peak seedling emergence in April or October precludes seedling establishment and displacement of native species.

Biology studies revealed that established rosettes move resources to an expansive taproot system until late in the fall (Bentivegna 2006). The application of systemic herbicides in late fall should result in accumulation in teasel roots, ultimately increasing plant response. During the time that plants are bolting and prior to flowering, much of the resources in the taproot are utilized to form stems and flowers. Using this knowledge, teasel plants can be mowed prior to flowering, thus utilizing valuable plant resources and reducing potential seed production.

Detection

Weeds are not distributed uniformly in natural settings; instead they occur in patches or follow patterns of tillage or crop harvest. The aggregation of weeds depend upon several factors including: seed dispersal; soil moisture, type, topography, nutrition and pH, etc.; and competition with other species (Shaw 2005). Seed dispersal for cut-leaved teasel, a large seeded broadleaf, is within 1.5 meters around parent plants, resulting in the patches observed for infested areas. The distinct patches for teasel, coupled with plants that exhibit a distinctive white flower at a time when few other flowering plants are observed in mid-Missouri (mid-July), contribute to the potential for detection of cut-leaved teasel using remote sensing. Lass et al. (2005) reported that

phenological changes (e.g. flowering) throughout the year determine the ability to differentiate among species using spectral reflectance (Lass et al. 2005)

Individual plant control during the arrival and establishment stages of invasion increases the success in reducing spread to new areas (Navaratnam and Catley 1986). Early detection can be conducted by field surveys. However, the high speeds and dense traffic along highways poses a risk to individuals in that area remote sensing can be conducted for obtained for many habitats and over larger areas in less time than field surveys (Underwood et al. 2003)

Digital image processing can result in a classification map that demonstrates weed infestations along the flight line (Sheley and Petroff 1999). Remote sensing, using hyperspectral images, was used to detect small infestations of leafy spurge (*Euphorbia esula* L.) (Glenn et al. 2005) and spotted knapweed (*Centarea maculosa*) (Lass et al. 2005). In addition, the use of digital images serves as a resource to monitor changes in weed populations after control measures are implemented. Shaw (2005b) suggests that remote sensing data should be utilized as a management tool and not simply as a problem-solving instrument.

Management

Management of invasive plants involves reducing the impact of the invasive plant where present, as well as preventing the spread to new areas (Weber 2003). The key to management of cut-leaved teasel is to break the life cycle in as many places as possible (Figure 6.2). For example, herbicides reduce the number of rosette plants, while mowing

reduces seed production. Establishment of a competitive desirable species in areas previously infested with cut-leaved teasel can serve to compete with emerging seedling plants, further reducing the level of infestation. Solecki (1993) has identified that elimination of rosette plants and the prevention of seed spread are keys to teasel management

Cut-leaved teasel colonizes many sites along Interstate Highway (I-70) in Missouri. Although seed is dispersed naturally around the parent plant (Werner 1975a), seed is continuously spread to new sites throughout other means such as mowing and water. Although cut-leaved teasel is a noxious weed in Missouri, the number of hectares infested and the wide distribution of infested sites suggests that reducing range expansion (Figure 6.3) will require a significant amount of time and resources. In addition, the reduction of teasel infestations will require the establishment of desirable species in treated areas to preclude encroachment of other undesirable species or the re-establishment of teasel.

Chemical management of cut-leaved teasel demonstrated that aminopyralid and metsulfuron were successful in the reduction cut-leaved teasel infestation by >90% (Chapter 5). In addition, aminopyralid reduced new seedling infestations, providing promise for reducing range expansion and establishment (Figure 6.3).

Desirable grasses were established to prevent new seedling emergence of cut-leaved teasel in infested areas. Tall fescue and Canada wildrye provided greater than 95% coverage of areas previously infested with cut-leaved teasel (Chapter 5). Establishment of desirable grasses precludes the use of environmental resources by other undesirable species (Sheley and Petroff 1999). A number of researchers have documented how the

introduction of competitive, desirable plant species can exclude weeds (Aldrich and Kremer 1997, O'Donnell and Adkins 2005, Sheley and Petroff 1999, Sheley and Bates 2008). Following the establishment of desirable species in areas previously occupied by invasive plants, some management is necessary to ensure the success of desirable plants.

Conclusion

Invasive plants invoke economic, environmental, or human harm (Zimdahl 2007). Related to economic impacts, invasive plants cost more than 27 billion a year in lost crop production reduced property values, and revenues to control (Pimentel et al. 2005). For the environmental and human concern, invasive plants reduce biological diversity, wildlife habitat, and stability of soil, while increasing herbicide use, pest and disease incidence, contamination of nutrients and soil in surface water, and exposure of humans and livestock to health risks (Czarapata 2005).

It is necessary to control invasive plants, but their eradication is almost impossible. Integrated management of cut-leaved teasel has the potential to reduce the invasiveness of this weed in Missouri.

With knowledge regarding both the biology as well as the location of a target weed, it is possible to apply herbicides in the specific time of the year and locations. In this way, the most efficient herbicide is spread at the optimum time, which can reduce up to 60% of the chemical required (Shaw 2005). The concept of Site-Specific Weed Management (SSWM) involves best management techniques not only in the locations where cut-leaved teasel is present currently, but also in areas that may be targeted for

invasion (Shaw 2005a, 2005b). This study demonstrated that SSWM for cut-leaved teasel is possible. In addition, weed prevention keeping a good stand of desirable plant must be considered to avoid new weed infestation (Aldrich and Kremmer 1997).

LITERATURE CITED

- Aldrich R.J. and R.J. Kremmer. 1997. Principles in weed management. Iowa State University Press, Ames, IO. 455 p.
- Bentivegna D.J. 2006. Biology and management of cut-leaved teasel (*Dipsacus laciniatus* L.) in Central Missouri. M.S. University of Missouri. 67 p.
- Czarapata E.J. 2005. Invasive Plant of the Upper Midwest. An illustrated guide to their identification and control. The University Wisconsin press. Madison, WI. 215p.
- Glenn N.F., J.T. Mundt, K.T. Weber, T.S. Prather, L.W. Lass, and J. Pettingill. 2005. Hyperspectral data processing for repeat detection of small infestations of leafy spurge. *Remote Sensing of Environment* 95:399-412.
- Lass L.W., T.S. Prather, N.F. Glenn, K.T. Mundt, and J. Pettingill. 2005. A review of remote sensing of invasive weeds and example of the early detection of spotted knapweed (*Centaurea maculosa*) and babysbreath (*Gypsophila paniculata*) with a hyperpectral sensor. *Weed Science* 53:242-251.
- Myers J.H. and D.R. Bazely. 2003. Ecology and control of introduced plants. Cambridge University press. Cambridge, UK. 313 p.
- Navaratnam, S.J. and A. Catley. 1986. Quarantine measures to exclude plant pests?. *in*: R.H. Groves and J.J. Burdln eds. The ecology of biological invasion. Cambridge University Press, Cambridge and New York. Pp 106-120.
- O'Donnell C. and S.W. Adkins. 2005. Management of parthenium weed through competitive displacement with beneficial plants. *Weed Biology and Management* 5:77-79.

- Pimentel D., R. Zuniga, and D.Morrison. 2005. Update on the environmental and economic cost associated with alien-invasive species in the Unites States. *Ecological economics* 52:273-288.
- Shaw D.R. 2005a. Remote sensing and site-specific weed management. *Frontiers in Ecology and Environment* 3:526-532.
- Shaw D.R. 2005b. Translation of remote sensing data into weed management decisions. *Weed Science* 53:264-273.
- Sheley R.L. and J.K.Petroff. 1999. Biology and management of noxious rangeland weeds. Oregon State University Press, Corvallis, OR. 438 p.
- Sheley R.L. and J.D. Bates. 2008. Restoring western juniper (*Juniperus occidentalis*) infested rangeland after prescribed fire. *Weed Science* 56:469-476.
- Simberloff D. 2003. How much information on population biology is needed to manage introduced species? *Conservation Biology* 17:83-92.
- Solecki M.K. 1993. Cut-leaved and common teasel (*Dipsacus laciniatus* L. and *D. Sylvestris* Huds.): profile of two invasive aliens. *in*: McKnight, B.N. ed., *Biological Pollution: The Control and Impact of Invasive Exotic species*. Indiana Academy of Science, Indianapolis. IN. Pp 85-92.
- Terres J. K. and B. Ratcliffe. 1979. Teasel, as in tease. *Audubon*. 9:108-109.
- Underwood E., S.Ustin, D.DiPietro.2003. Mapping non-native plants using hyperspectral imagery. *Remote Sensing of Environment* 86:150-161.
- Weber E. 2003. *Invasive plant species of the world. A reference guide to environmental weeds*. CABI publish, Cambridge, MA. 548 p.

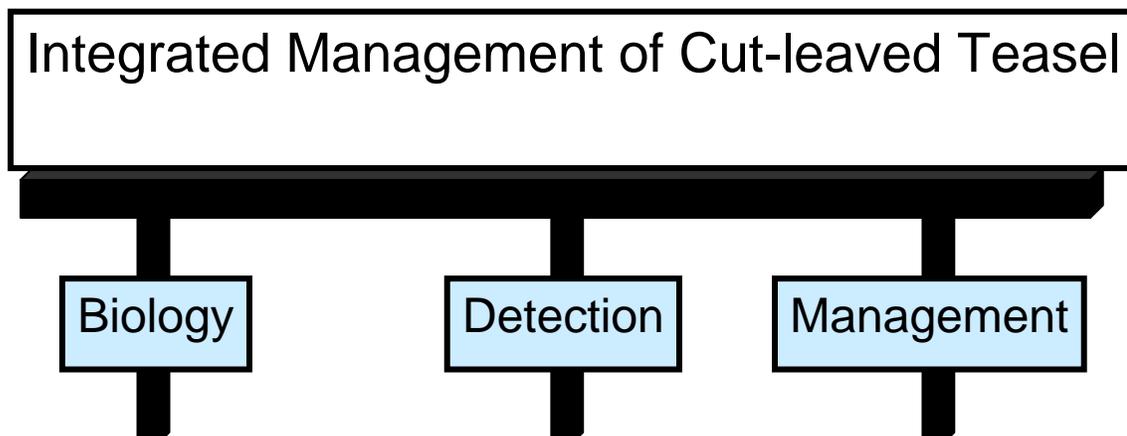
Werner P.A. 1975a. A seed trap for determining patterns of seed deposition in terrestrial plant. Canadian Journal of Botany 53:810-813.

Werner P.A. 1975b. The biology of Canadian weeds 12. *Dipsacus sylvestris* Huds. Canadian Journal of Plant Science 55:783-794.

Werner P.A. 1977. Colonization success of a “biennial“ plant species: experimental field studies of species cohabitation and replacement. Ecology 58:840-849.

Zimdahl, R.L. 2007. Fundamentals of weed science. Academic press. Burlington, MA . 666 p.

Figure 6.1. Three pronged approach for the integrated management of cut-leaved teasel.



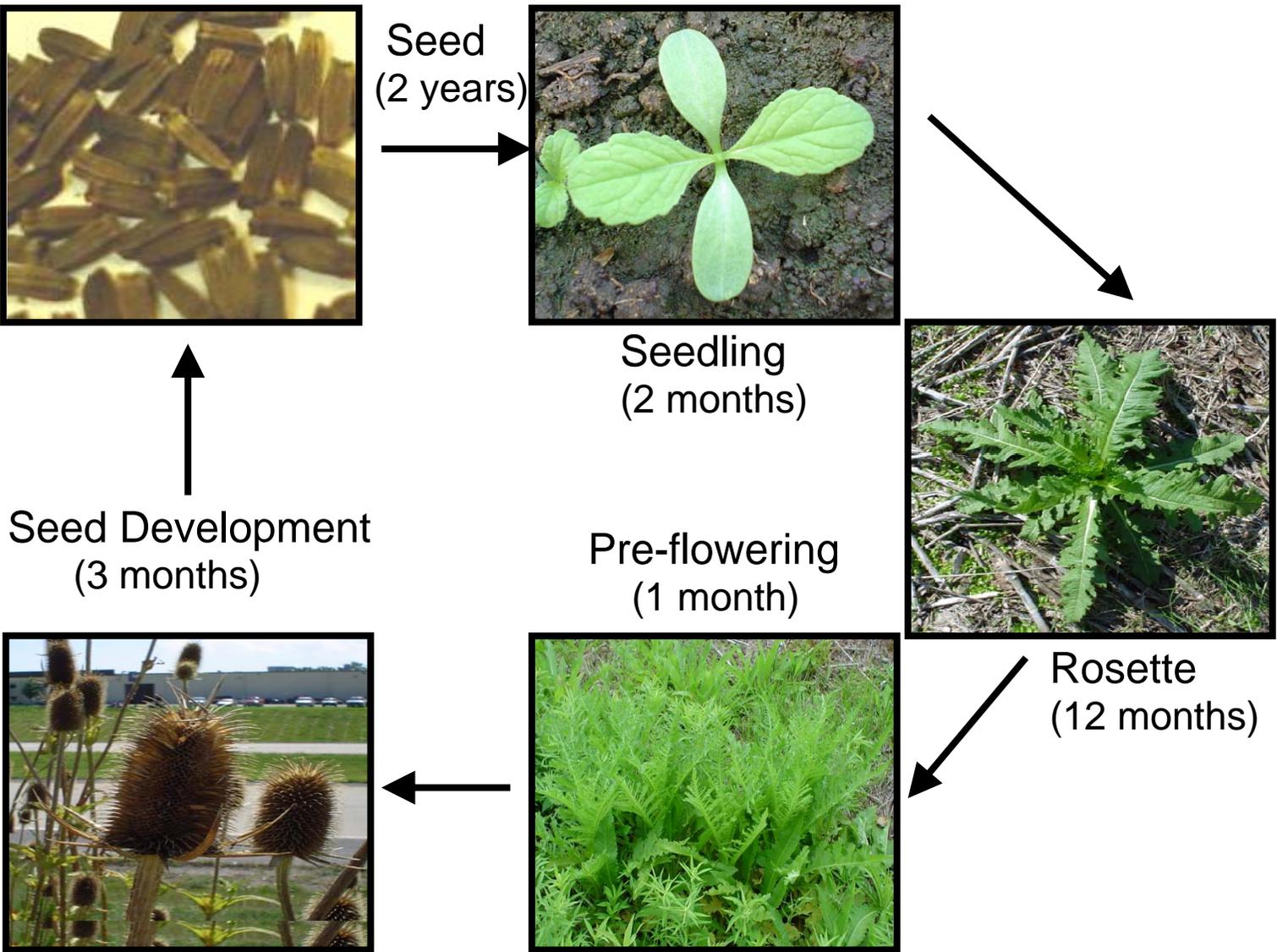
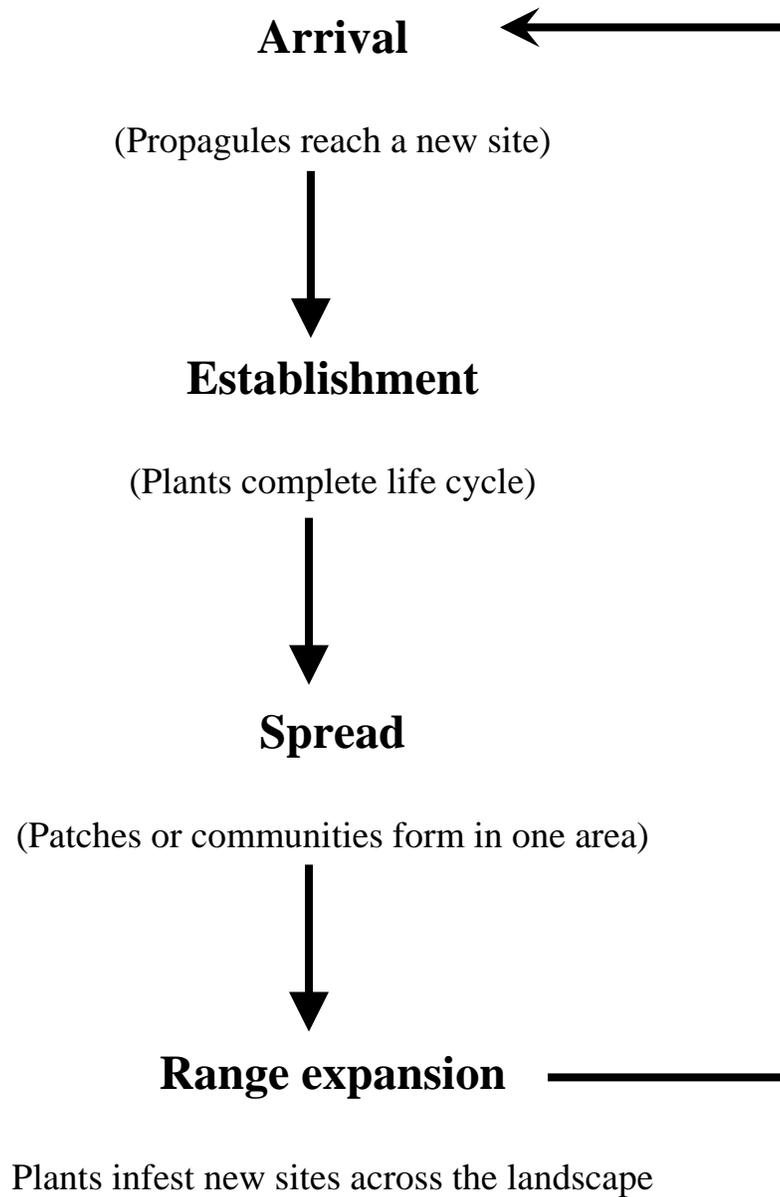


Figure 6.2. Representative Cut-leaved Teasel (*Dipsacus laciniatus* L.) life cycle in central Missouri

Figure 6.3. Steps in the successful invasion of non-native species (Adapted Weber 2003)



APPENDIX

Table A.1. Error matrix of the classification map in Exit 89 section of the highway I-70 using maximum likelihood classification on hyperspectral image (63 bands).

Class	Cut-leaved teasel	Grass+ Broadleaf	Bare Soil	Tree+ Shrub	Water	Total
Cut-leaved teasel	41	5	4			50
Grass+Broadleaf	2	47	1			50
Bare Soil	2	2	46			50
Tree+ Shrub	1	2		47		50
Water					50	50
Total	46	56	51	47	50	250

Kappa Coefficient of Agreement.

Cut-leaved teasel.....0.7794

Grass+Broadleaf..... 0.9227

Bare Soil..... 0.8995

Tree + Shurb..... 0.9261

Water..... 1

Table A.2. Error matrix of the classification map in Exit 89 section of the highway I-70 using maximum likelihood classification on hyperspectral image (12 bands).

Class	Cut-leaved teasel	Grass+ Broadleaf	Bare Soil	Tree+ Shrub	Water	Total
Cut-leaved teasel	32	7	3			42
Grass+Broadleaf	7	43	1	1	1	53
Bare Soil	6	3	47	1	1	58
Tree+ Shrub	1	3		45	1	50
Water					47	47
Total	46	56	51	47	50	250

Kappa Coefficient of Agreement.

Cut-leaved teasel.....0.7082

Grass+Broadleaf..... 0.7569

Bare Soil..... 0.7617

Tree + Shurb..... 0.8768

Water..... 1

Table A.3. Error matrix of the classification map in Exit 89 section of the highway I-70 using spectral angle mapper classification on hyperspectral image (63 bands).

Class	Cut-leaved teasel	Grass+ Broadleaf	Bare Soil	Tree+ Shrub	Water	Total
Unclassified			6	2	12	20
Cut-leaved teasel	29	7	3			39
Grass+Broadleaf	15	43	2	3		63
Bare Soil	1	4	40			45
Tree+ Shrub	1	2		42		45
Water					38	38
Total	46	56	51	47	50	250

Kappa Coefficient of Agreement.

Cut-leaved teasel.....0.6858

Grass+Broadleaf..... 0.5909

Bare Soil..... 0.8604

Tree + Shurb..... 0.9179

Water..... 1

Table A.4. Error matrix of the classification map in Exit 89 section of the highway I-70 using spectral angle mapper classification on hyperspectral image (12 bands).

Class	Cut-leaved teasel	Grass+ Broadleaf	Bare Soil	Tree+ Shrub	Water	Total
Unclassified			2		4	6
Cut-leaved teasel	15	4	3	1	2	25
Grass+Broadleaf	29	49	3	5	2	88
Bare Soil	1	2	43		2	48
Tree+ Shrub	1	1		41		43
Water					40	40
Total	46	56	51	47	50	250

Kappa Coefficient of Agreement.

Cut-leaved teasel..... 0.5098

Grass+Broadleaf..... 0.4289

Bare Soil..... 0.8691

Tree + Shrub..... 0.9427

Water..... 1

Table A.5. Error matrix of the classification map in Lamine section of the highway I-70 using maximum likelihood classification on hyperspectral image (63 bands).

Class	Cut-leaved teasel	Grass+ Broadleaf	Bare Soil	Tree+ Shrub	Water	Total
Cut-leaved teasel	42	8				50
Grass+Broadleaf	5	42	2	1		50
Bare Soil		2	47	1		50
Tree+ Shrub		1		49		50
Water				5	45	50
Total	47	53	49	56	45	250

Kappa Coefficient of Agreement.

Cut-leaved teasel..... 0.8030

Grass+Broadleaf..... 0.7970

Bare Soil..... 0.9254

Tree + Shrub..... 0.9742

Water..... 0.8780

Table A.6. Error matrix of the classification map in Lamine section of the highway I-70 using maximum likelihood classification on hyperspectral image (12 bands).

Class	Cut-leaved teasel	Grass+ Broadleaf	Bare Soil	Tree+ Shrub	Water	Total
Cut-leaved teasel	34	5				39
Grass+Broadleaf	12	44	3	3		62
Bare Soil	1	2	46	2	1	52
Tree+ Shrub		2		47		49
Water				4	44	48
Total	47	49	49	56	45	250

Kappa Coefficient of Agreement.

Cut-leaved teasel.....0.7794

Grass+Broadleaf..... 0.6316

Bare Soil..... 0.5965

Tree + Shurb..... 0.9474

Water..... 0.8421

Table A.7. Error matrix of the classification map in Lamine section of the highway I-70 using spectral angle mapper classification on hyperspectral image (63 bands).

Class	Cut-leaved teasel	Grass+ Broadleaf	Bare Soil	Tree+ Shrub	Water	Total
Unclassified		1	14	6	42	63
Cut-leaved teasel	17	5				22
Grass+Broadleaf	28	42	6	2	1	79
Bare Soil			28			28
Tree+ Shrub	2	6		47		55
Water					3	3
Total	47	54	48	55	46	250

Kappa Coefficient of Agreement.

Cut-leaved teasel.....0.7201

Grass+Broadleaf..... 0.4026

Bare Soil..... 1

Tree + Shurb..... 0.8135

Water..... 1

Table A.8. Error matrix of the classification map in Lamine section of the highway I-70 using spectral angle mapper classification on hyperspectral image (12 bands).

Class	Cut-leaved teasel	Grass+ Broadleaf	Bare Soil	Tree+ Shrub	Water	Total
Unclassified			8	5	7	20
Cut-leaved teasel	6	6				12
Grass+Broadleaf	33	37	7	4	18	99
Bare Soil		3	30		1	34
Tree+ Shrub	8	8		46	2	64
Water			3		18	21
Total	47	54	48	55	46	250

Kappa Coefficient of Agreement.

Cut-leaved teasel..... 0.3842

Grass+Broadleaf..... 0.2012

Bare Soil..... 0.8544

Tree + Shurb..... 0.6394

Water..... 0.8249

VITA

Diego Javier Bentivegna was born in Bahia Blanca, a city port in the south of Buenos Aires State, Argentina. He enrolled at catholic Don Bosco High School where he finished in 1986. In 1993, he obtained his Bachelor degree in Agronomy, and in 1999, he obtained his second degree as Professor in Agrarian Science, both degree in the Universidad Nacional del Sur, Bahia Blanca, Argentina (UNS). In addition, in 2001 he finished his Master Degree in aquatic weeds, specially working with biology and management of *Potamogeton pectinatus* L. in irrigation canals (UNS). From July 1995 to 2003, he was technician working as Professional in the Commission of Scientific Researches of the Buenos Aires State (CIC). Also, he was the head of the meteorological office that contains five meteorological stations. In 2003, he began his graduate studies at the University of Missouri in Columbia, MO (Mizzou). In 2006, he finished his second master degree about biology and management of *Dipsacus laciniatus* L. at Mizzou. In 2008, he earned his Degree of Doctor in Philosophy in Plant Insect and Microbial Sciences at Mizzou. He had given more than twelve conferences and courses about weed management in non-crop lands. He has four publications in scientific magazines and he had produced more than seventeen communications to Congresses. He is currently working at CERZOS (Center of Renewable Natural Resources of the Semiarid Zones) Bahia Blanca, Argentina.