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Management Practices for Weed Control in Roadway Rights-of-Way

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16. Abstract (Limit: 200 words)

By law, Departments of Transportation are required to control noxious weeds along highway rights-of-way (ROWs). Since 2000, District 4 (D4) of Minnesota Department of Transportation (Mn/DOT) adopted a survey design consisting of n= 7, 3-mi segments to quantify infestations of Canada thistle (*Cirsium arvense* (L.)(Scop.), leafy spurge (*Euphorbia esula* L.), and poison ivy (*Toxicodendron radicans*) in chosen regions of the district. In 2004 and 2005, a second survey design was added to see if stratification by ecozone in D4, and greater numbers of 1/4-mi segments could improve precision. Comparison of matching sample statistics from the 3-mi and 1/4-mi plans in each year indicated the two plans yielded equivalent estimates of mean acres per roadway mile of each weed (α = 0.05). However, precision at the district level was much greater in all cases with the 1/4-mi plan. In addition, weed abundances varied substantially among ecozones ($\alpha < 0.05$); this knowledge will allow managers to direct control efforts to problem areas. Finally, a combination of computer based mapping and resampling of the 1/4-mi segments observed in the two years suggests that additional improvements in precision and efficiency are likely to occur if segment lengths are shortened to 125’ or less. Shorter segments would reduce inspection costs, increase sample sizes, improve precision, and possibly allow conversion from an area-measurement approach to one based on presence or absence of chosen weeds in selected segments. Plans are underway to compare the latter two approaches in 2007.

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Management Practices for Weed Control in Roadway Rights-of-Way

Final Report

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Executive Summary

Presence of noxious weeds can contribute to degradation of the economic value of rangelands, threaten the structure and functioning of ecosystems, and have negative impacts on landscape biodiversity. Occurrence of these species in roadside rights-of-way can affect driver safety, pavement maintenance and storm water management. State and federal laws require all state and federal agencies to manage noxious species on the prohibited state and federal lists. Agencies often have unique management objectives; hence control measures, which may not always be in harmony with the management goals of other agencies. For example, the need for maintenance of a clean, clear-cut roadside environment may be in conflict with the need for conservation / preservation of certain vegetation species; or chemical control measures embraced by one agency, such as the federal highway administration (FHWA), may not meet approval of forest service officials for use in areas where noxious weed infestations may extend outside of road easements. The need to economize is often in opposition to environmental concerns.

For managers to make informed decisions on appropriate measures for control of invasive species, data providing accurate location of noxious invasive species is crucial. This information is often obtained by conducting inventories, which due to the patchy and disperse nature of weed infestations, as well as large extent of concerned areas, can be costly and time consuming to undertake. Alternative techniques of acquiring this data involve use of small sample surveys to represent large areas.

Beginning 2000, District 4 of the Minnesota Department of Transportation (Mn/DOT) adopted use of small sample surveys to estimate district-wide infestation of the three problematic species (Canada thistle, leafy spurge and poison ivy). Sampling survey was conducted at seven (fixed-location) three-mile segments selected in rights-of-way within district highways. Questions regarding the validity of the adopted sample number and size prompted formulation of the current study.

The main objective of this study was to develop a statistically valid method to quantify the extent and distribution of weeds in the entire (Mn/DOT's Distrct 4) study area.

New sampling procedures, employing a larger number of smaller size segments selected using stratified random sampling, were developed and tested. This new design adopted data selected while taking into consideration stratification based on ecological zone differences within the study area. Data obtained from the new design was applied in evaluating performance of the current Mn/DOT's sampling design. The data were further used to formulate methodologies for selection of an optimum sample size, comprising minimum number of sampling units for minimum variance in survey data per dollar spent in the surveys. During the course of this study, a survey questionnaire was also administered to personnel from different state and federal agencies, to gather information on methods employed in surveying and mapping invasive species.

The analysis of the mean infested acres-per-mile data recorded following the two sampling designs yielded mixed results. The district-wide acres-per-mile data recorded in

2005 showed significant differences (σ =0.05) in only the poison ivy means. Mean acre-per-mile of Canada thistle and leafy spurge obtained using the two sampling designs did not yield significant (σ =0.05) differences. However, similar data recorded in 2004 showed significant differences for all species. In all cases, values obtained using the current Mn/DOT sampling design (3-mi segments) were consistently lower compared to those from the new (1/4-mi segment) design. The variances of means obtained in the application of the current Mn/DOT sampling method were much larger than those of the new design, implying lower sampling precision using this design.

Analysis of data across ecological zones showed significant differences among means from the two sampling designs. The obtained results revealed the new design to be better suited in representing infestation across diverse landscapes. Sample selection needs to take into consideration differences in land and environmental characteristics, such as ecological zones, which are known to influence infestation by noxious species.

Data obtained in the application of the new sampling designs were applied to optimal allocations of future sampling surveys among 9 strata (ecological zone and type of highway combinations) varied with weed species and year. For Canada thistle (the most abundant weed), allocations were similar between years. Allocations for leafy spurge and poison ivy were more erratic between years.

Finally, we found a 1/20th-mi segment length to be more efficient in conducting surveys to meet Mn/DOT District 4's needs. Further analysis has indicated that a more efficient unit size may be even smaller.

Regarding future surveys by Mn/DOT District 4, the following recommendations have been suggested:

- Mn/DOT should build a weed monitoring program around their worst weed problem, Canada thistle
- Sampling should involve stratification, taking into account ecological regions and roadway types (whether divided, with a median, or not)
- That Mn/DOT should use the smallest feasible sample unit (road segment length), the 1/20th- mile scored highest relative net precision from analysis of the two years' data
- The allocations in future years should be revised sequentially, to use previous year's data to plan the following year's surveys

Chapter 1

Survey Report on Methods for Management of Roadside Weeds

6.1 Introduction

Management of weeds along roadways rights-of-way (ROWs) has significant economic and environmental implications. Selection of sustainable methods for weed management requires accurate information on weed infestation by location, distribution and population dynamics. Experience has shown that different organizations adopt different approaches and methodologies for conducting surveys and inventory of weed infestations.

A survey was undertaken to gather information on methods used by state and federal agencies in Minnesota and other select states in United States to conduct surveys, mapping and management of weeds. Personnel contacted and interviewed included heads of sections and/or departments, weed biologists, researchers, supervisors, and others involved in decisions regarding weed management in the agencies. Valuable information was gathered, revealing both diversity and similarities in methods employed by the many contacted agencies.

This chapter offers a summary of responses obtained from the telephonic survey administered on these state and federal personnel charged with responsibility of managing weed infestations in the lands under their jurisdiction across the United States.

Questions sought to gain insights on both the type and procedures of the adopted survey methods, and on criteria used in selection of control measures, , problems associated with application of given control measure(s), and finally, whether any of the agencies are conducting economic cost analysis of the adopted control measures.

6.2 Responses to questions on weed management strategies

Survey questions:

The following five questions were posed to all respondents contacted. The responses to each question are presented verbatim in the consequent sections.

1. What methods/techniques do you use in conducting weed inventory surveys of land under your agency's management?
2. What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?
3. What criteria do you use to select the most appropriate method to manage these weeds?
4. What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?
5. How do you measure the cost effectiveness of your weed management system?

The following is a summary of recorded responses from interviews completed in MONTH of YEAR:

6.2.1 Minnesota Department of Agriculture (MDA)

The following officers were interviewed at the MDA:

Contact 1: Mary J. Hanks
Position: Supervisor, Sustainable Agriculture and Integrated Pest Management (IPM)

Contact 2: Anthony Cortilet
Position: Research Scientist, Sustainable Agriculture and IPM

Contact 3: Monika Chandler,
Position: Research Scientist, Bio-control, Sustainable Agriculture and IPM

The above personnel at the Sustainable Agriculture and Pest Management unit of the MDA responded to the interview with tremendous enthusiasm and cooperation. Useful information was availed, besides their providing references, publications and website informational sources.

In general, the MDA is engaged in an effort to develop a statewide inventory and map of weed infestations. According to Cortilet, there still are many exotic invasive species coming into the state. There is, therefore, need for a comprehensive, mobile database on these invasive species. , He further observed that there are critical questions being asked: What the actual problem with weed presence is; the number of acres of problem weed species present in Minnesota.

Hanks availed a hard copy of a publication "Integrated Pest Management and Sustainable Agriculture for State-owned Lands", a cooperative effort between MDA and MN-DNR. Chandler made reference to the excellent work done by the state of Montana in weed mapping and creation of a valuable database for counties, all published online; she provided the website for further information.

Question 1: What methods/techniques do you use in conducting weed surveys in land under your agency's management?

MDA is working on a sub-sampling method. Currently, a survey is conducted by driving to select county/locations, and selecting a road randomly to drive on and conduct a survey/inventory. Data is collected and recorded using a hand-held PDAs (HP-IPAQ), with wireless connection to (Bluetooth enabled) GPS (Holux) unit. The PDA is pre-loaded with digital orthoquadrat (DOQs) maps for the areas being surveyed, which may be displayed at will. The touch screen of the unit permits data entry by tracing observed infestations on the DOQ zoomed to the site. Alternatively, the operator may chose to map the infestations by walking around observed patches, with the GPS unit recording spatial information on the circumvented patches. The surveys and field work conducted by MDA in 2004 was mainly to this newly acquired equipment.
Question 2: What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?

This unit of MDA is involved only in research on bio-control and IPM, and not in weed control. I was referred to the Agronomy and Plant Protection group, responsible for weed management.

Question 3: What criteria do you use to select the most appropriate method to manage these weeds?

Research funding is provided to the Department only for projects on use of bio-control methods.

Question 4: What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?

None.

Question 5: How do you measure the cost effectiveness of your weed management system?

The Department has tried to compare per acre cost in using bio-control against use of herbicides for management of leafy spurge and purple loose strife. Findings of the comparisons were not provided in this interview.

6.2.2 Mn/DOT Roadside Management and Pest Information

Contact: Paul Walvatne
Position: Senior Transport Program Supervisor

The Minnesota Department of Transportation currently does not have a state-wide (or District-wide) standardized method for weed management. State law requires control of the 11 prohibited noxious weeds and other weeds that are elevated to prohibited noxious weed status on a county by county basis through County Board action. MN/DOT Districts and maintenance areas do their best to establish pro-active weed control programs as well as respond to complaints from adjacent landowners. Although Canada thistle remains the top weed statewide, there is a great variance in other weed species deemed problematic from one part of the state to another, hence management methods would differ significantly across the state.

To date, MN/DOT has yet to develop a comprehensive State database on weed infestations. However, the agency plans to roll out a statewide spray applicator record system in spring 2005 with the goal of achieving consistency statewide and the ability to retrieve data on the acreage of weeds sprayed by species as well as by chemical. This system will mesh with the PPMS (Program and Project Management System) program currently used to track salt usage statewide.

Cutbacks in the extent and frequency of roadside right of way mowing in the last three decades has led to nearly a two-fold increase in acres sprayed on an annual basis, from approximately 5% of the 175,000 acres of green space to nearly 10% on an annual basis. Maintenance budgets play a role in dollars available for roadside weed control, especially when long, snowy winters deplete the budget.

Question 1: What methods/techniques do you use in conducting weed inventory surveys of land under your agency's management?

In the early 1990's as a spin-off from the Business Planning efforts of the Area Maintenance Engineers, MN/DOT maintenance staff conducted surveys on weed extent by conducting windshield surveys of randomly selected segments of roadsides. Results were tabulated to fit a continuum from 1 to 10 with a high rating indicating relatively weed free roads. Typically the surveys showed results from 8 to 10 and oftentimes surprised the supervisors and applicators that travel the roads on a regular basis.

Supervisors and applicators use a combination of recent observations and sub-area herbicide use or weed mowing extent to determine the weed control activity levels for the upcoming growing season.

Recently technical advisors to District maintenance operations stressed the importance of "early detection and rapid response" to small infestations of weeds that have potential to spread quickly to become a bigger problem on roadsides. Weeds considered a problem are located, mapped, and the maps used in planning and implementing control measures. For example, in the Twin Cities Metro Area, many state roadsides in the southwest suburbs (e.g. Eden Prairie and Minnetonka) express heavy infestations of leafy spurge. Spraying infested areas beyond the bottom of the ditch is a waste of resources and better left to biological control methods with beneficial insects. On the other hand many other metro roadsides are relatively free of leafy spurge. Scattered and very small infestations are beginning to express on roadsides where mowing activity has gradually diminished in extent and frequency. Mapping these infestations and insuring teamwork and diligence between the mower operators and weed spray applicators remains the only hope for keeping the infestations small and possibly even eradicating them! So far, there is no metro-wide mapping of new or existing patches of weed.

Mn/DOT District 4 maintenance staff pioneered mapping as logical extension of the windshield surveys of the 1990's. They began mapping three mile segments of various roadsides in their District with the hopes of documenting the need for consistent and adequate equipment and supplies for weed control and to determine whether they were gaining or losing in their weed control program. Their efforts provided good background information and led to the interest in expanding the effort to more formal research through the University of Minnesota.

Question 2: What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?

Where difficult weeds are already well established the focus is on how to control the weeds using a combination of mechanical, chemical, cultural, and biological methods and good timing for effective management. Mowing and spraying lead the list of activities, however; starting in the late 1980's through the present; cultural and biological methods have played larger roles.

A typical tactic is to spot spray all Canada thistle prior to bloom. Due to the extensive nature of infestations it becomes impossible to spray all infestations before bloom. Therefore some infestations are mowed with the intent to spray out re-growth later in the season. Mower operators are cautioned to clean mower decks before moving to uninfested locations. The caution, however, is not being heeded by most.

Cultural methods such as seeding new construction sites to native prairie vegetation and converting existing cool-season grass roadsides to native prairie have been used extensively, especially in the central areas of the state in the vicinity of St. Cloud. Mn/DOT Maintenance Area 3B (St. Cloud area) boasts over 1000 acres of roadside prairie. Mn/DOT seed mixes contain a high percentage of prairie grass and wildflower seed. One of the drawbacks to the use of native seed mixes is their slow establishment which can lead to early erosion problems and non-compliance with National Pollution Discharge Elimination System (NPDES) and MS4 requirements. Attention to this problem has temporarily slowed or reduced the use of native prairie vegetation in roadside seed mixes.

Bio-control is also used extensively for leafy spurge, purple loosestrife and spotted knapweed. Well over 1,000,000 beetles have been released since the early 1990's. Cooperators select beneficial insect release sites based on weed extent within and outside the roadside right-of-way and the likelihood of roadside disturbance from mowing, road construction, or spraying activities.

Early detection and rapid deployment of effective control methods will be key elements of efforts to control or eradicate new infestations of invasive weeds.

<u>Question 3</u>: What criteria do you use to select the most appropriate method to manage these weeds?

Effective control to stop the spread of infestation to new areas is an important weed management goal to Mn/DOT. Environmental sensitivity, control effectiveness, economic effectiveness, and political ramifications of a measure are key considerations. Toxicity of control chemicals and economic considerations often encourage use of alternative methods, including cultural and biological controls.

<u>Question 4</u>: What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?

Negative impacts of chemicals on desirable woody plants and native wildflowers were a major issue. Mowing is expensive, but also has been proven responsible for spread of weeds to new areas, by seed or plant fragments. Cultural and biological methods and activities usually take years to produce effective results; hence do not meet customer expectations.

<u>Question 5</u>: How do you measure the cost effectiveness of your weed management system?

Cost effectiveness is determined for each control measure by determining the cost of each measure applied to control known acreage of infestation in the District, or entire state. Sometimes, the best measure of cost effectiveness is the number of complaints from the public or consumers. The University of Minnesota conducts an annual Omnibus survey to determine public acceptance of road and roadside condition. According to the latest Omnibus survey, (report available) the acceptance level is below the goal (7 in a scale of 1 to 10) for roadside attractiveness and weed control.

When pushed to rate in importance, control of weeds in roadsides, having clear roads in winter, or smooth roads all year round; respondents rated clear roads in winter, and smooth roads all year round as the highest priorities. Studies show that the public like neat and attractive roads; however, when there is not enough money to go around then expenditures on roadside activities has to be reduced.

Minnesota Department of Transportation (Mn/DOT)

Contact: Tom Jacobson
Position: Landscape Specialist (District 1)

MN/DOT, District 1 has for the last eighteen (18) years tracked weed infestation in rights-of-way (ROWs) of roads in the District. Infestation maps for the District's ROWs have been constructed referenced to the mile posts. The main weeds of interest have been leafy spurge and purple loosestrife. Jacobson has been working for years mainly in District 1A (Duluth), but recently has added District 1B (Virginia) under his jurisdiction. His knowledge on location of infestations by these two weed species, among others, is extensive in this District. Physical maps have been constructed for existing and new infestations within the Duluth sub-District. Efforts to complete the same for the Virginia sub-District are ongoing.

There currently is collaboration (mainly data sharing) with the US Forest Service, who are conducting complete inventory and mapping of noxious weeds in the Superior National Park region. Both agencies use similar surveying and mapping equipment and protocol. The purpose of the collaboration is mainly to assist each other with construction of comprehensive maps and database of noxious weeds in the District.

<u>Question 1</u>: What methods/techniques do you use in conducting weed inventory surveys of land under your agency's management?

MN/DOT's District 1 is using GIS/GPS systems to map weed infestation along its highways' rights-of-way. Trimble Pro-XR GPS units are used for data collection, which are being incorporated to create weed database using GIS (ArcView/ArcMap) software. The US Forest Service has adopted similar protocol.

Jacobson explains: "Perhaps a bit of history will help explain this one. Most of our noxious weeds are not tracked or mapped by any means. Weeds such as Canada thistle, Perennial Sow Thistle and Bull Thistle are prevalent on all our District roads and mapping them would be a massive undertaking. Poison Ivy, Leafy Spurge and Purple Loosestrife are found in mostly small containable quantities and they are the primary weeds we have mapped by written documentation. In the past three years I have started to use a borrowed Trimble Pro XR to map Purple Loosestrife and Leafy Spurge areas. My duties are District wide, so I map these as a side to my other duties as I travel and have the Trimble available. As I find out about new locations for Plumeless thistle, spotted knapweed or other invasive plants, I try to map them as well. I have County Agriculture Inspectors, County Engineers, DNR, U. S. Forest Service, Tribal officials, Community Activists and the public in general helping me to watch for new infestations or plants, and as they are found they are now mapped in ARCMap. It's an on-going District-wide process which is limited by equipment and man-hours. We tried random sampling several years ago with the Mn/DOT Maintenance Business Practices Survey for noxious weeds. We found them to be very inaccurate with the diversity of landscapes we have in District 1 and the practice was abandoned. In brief, our weed data base is District-wide and limited to select species in which we find limited populations. "

Question 2: What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?

Due to budgetary limitations, the Department uses chemical control measures extensively. Apparently, though chemicals are usually costly, the amount of work completed per unit cost is lower than using other control measures. Purple loosestrife is being controlled by bio-control measures.

Question 3: What criteria do you use to select the most appropriate method to manage these weeds?

Economic (Budgetary) considerations are important. However, nature of infestation is more important. Large (contiguous) infestations and scattered patches are usually controlled by chemical measures. Jacobson explains: “I will expand this a little. There are many factors that determine treatment methods for our weed problems. In District 1, environmental concerns are a major determining factor since we have many sensitive areas to work around. The impact of each treatment method is considered before a treatment method is selected. We rely heavily on chemicals with some biological controls where applicable. In some cases mechanical controls are the only method considered.”

Question 4: What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?

Man power limitations are the biggest problem. Man power allocation is assigned to higher priority activities, such as roads operations, before noxious weed control, which is a lower priority.

Question 5: How do you measure the cost effectiveness of your weed management system?

Cost effectiveness has not been tracked. Management methods being adopted may not necessarily be the optimum ones, but rather the ones available at hand.

Minnesota Department of Natural Resources (DNR)

Contact: Luke Skinner
Position: Research Scientist, Invasive Species Program

Initial contacts with DNR yielded various names of possible officers to interview. These were Tim Loesch, who referred me to Steve Benson (GIS Specialist, DNR Wildlife Division), and finally Luke Skinner.

Skinner informed me that DNR manages approximately five million acres of land statewide. Mapping is conducted mainly on areas of interest, such as when the Department of wildlife is concerned with elevated levels of infestation by a given weed, e.g. Canada thistle.

Question 1: What methods/techniques do you use in conducting weed inventory surveys of land under your agency’s management?

The unit of the DNR which is concerned with invasive species management has adopted use of PDAs connected to a GPS unit for conducting weed inventories. Standardized protocols have been established for surveying terrestrial invasive plants. A statewide pilot project was carried out surveying various invasive plant species on state managed lands using a standardized monitoring protocol and centralized database. One of the initiatives was in SW Minnesota where Canada thistle is a weed of concern, and is currently being surveyed.

Question 2: What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?

Weed control measures being utilized are based on an integrated approach, depending on the situation and the weed in question. This includes manual, chemical, cultural and biological control methods.

Question 3: What criteria do you use to select the most appropriate method to manage these weeds?

Criteria being employed in selection of control measures include effectiveness of a measure on a problem weed, minimal non-target impacts, economic considerations (but only as a minor concern), and thirdly efforts to reduce chemical use.

Question 4: What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?

Primary lack of effectiveness of specific control measures (long-term control in particular), and inadvertent effects on non-target natives are some of the main problems encountered during application of control measures. In addition, labor and cost can be a problem.

Question 5: How do you measure the cost effectiveness of your weed management system?

Measure of cost effectiveness adopted by DNR – Invasive Species Program is mainly qualitative. The concern is protection of desirable native species plant diversity. To this end, a comparison is being performed to evaluate biological versus chemical control measures as one measure of effectiveness.

National Park Service (US Department of Interior)

By the writing of this report, we had not been able to reach and interview relevant personnel in this department.

United States Geological Survey

Personnel we contacted (Drs. Eileen M Kirsch and Yao Yin) could not participate in the survey as their responsibilities did not include weed management activities. Efforts to contact the officer in charge of Mapping and Remote Sensing (Dr. Larry Robinson), Upper Midwest Environmental Sciences Center (UMESC) Lacrosse, were not successful.

6.2.3 United States Geological Survey

Contact: Kevin Hop
Position: Team Leader, Vegetation Mapping Project, UMESC

Hop informed us that his team is involved in general vegetation mapping in National Parks. Color infrared maps, scales of 1:12,000, 1:15,000 and/or 1:24,000 are used. Stereoscopes are used in interpretation and classification of vegetation types, together with extensive ground *truthing*.

No further survey questions were addressed since this unit of the USGS is not involved in weed survey/mapping and management activities

6.2.4 Bureau of Land Management (US Department of Interior*)*

Contact: Jeff Walsh
Position:

Not been able to establish contact with Mr. Walsh.

6.2.5 Bureau of Indian Affairs (US Department of Interior)

Contact: None to date
Position:

6.2.6 Forest Services (US Department of Agriculture)

Contact: John Bell
Position: Engineer in charge, Forest Service Roads

Recommendations to contact Mr Bell received recently (as of date of compiling this report), and has yet to be reached

6.2.7 US Army Corps of Engineers

Contact: Ralph Augustine
Position: (In charge of wetlands)

This officer informed me that his unit (in charge of wetlands) was mainly concerned with surveying and identification of some target plant communities. These are mainly native and invasive species. Following the survey, the invasive are further categorized into either 'Aggressive' or 'Non-Aggressive' groups. This classification is, as terms suggest, based on how aggressive a species is in colonizing the site they have invaded. Surveys are usually conducted on sites which are planned for development by state, federal or private developer, or if it is to be filled by the Department of

Transportation. Weed control by the US Corps of Engineers is mainly solution oriented, hence selection of control measures at given locations may not be influenced by economic considerations.

Question 1: What methods/techniques do you use in conducting weed inventory surveys of land under your agency's management?

Surveys are conducted mainly on sites targeted for development. This is done by walking the area, identifying and mapping existing species. Weeds of concern are noted and their control specified in the permit.

Question 2: What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?

Control is customized per individual situation. Hand pulling and cutting, chemical, or fire are often employed.

Question 3: What criteria do you use to select the most appropriate method to manage these weeds?

Appropriate control methods are often specified with the permit given to the developer, who will be responsible for weed(s) control. Where the US Corps of Engineers are responsible for the control, their "solution oriented approach" dictates customization of measures to meet the objectives. Control measures are weed specific, and may range from use of chemicals or mechanical measures, to removal of soil layer containing seed.

Question 4: What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?

Not aware of any problems encountered during application of control measures.

Question 5: How do you measure the cost effectiveness of your weed management system?

US Corps of Engineers does not conduct cost effective analysis. Not aware whether those granted permits to develop an area, and are required to control weeds, perform cost effectiveness analyses.

Minnesota Pollution Control Agency (MPCA)

By the writing of this report, we had not been able to reach and interview relevant personnel in this department.

The main office informed me that MPCA it is not involved in weed management, instead referred me to Minnesota Department of Agriculture

Maryland State Highway Administration (MD, SHA)

Contact: Don Cober
Position: Team Lead Technical Services, Landscape Operations Division

The Maryland State Highway Administration has to date conducted weed inventory through data obtained from spray reports combined with windshield reports, which involves driving along the road, stopping and documenting data (weed name, infestation density, and area square feet) on encountered weeds. The MD-SHA is currently involved in project with Maryland DOT on control on Canada thistle.

Question 1: What methods/techniques do you use in conducting weed inventory surveys of land under your agency's management?

Estimations based on spray data (amount of chemical applied at given application rate) and wind shield report. The Department is in the process of involving consultants to assist them in establishing appropriate GPS-GIS technology for adoption.

Question 2: What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?

All thistle infestations are mowed, or sometimes, depending on the nature of infestation, chemicals (Transline or combination of Transline and 2-4-D), are applied. Some bio-control measures are being used on several weeds (but not Canada thistle, as those available have not been effective). Research on isolation of pseudomonas (which shows promise), is ongoing.

Question 3: What criteria do you use to select the most appropriate method to manage these weeds?

Timely mowing of roadsides at appropriate frequency (usually four times a year); isolated infestation patches have to be sprayed. Maryland laws require that thistles and Johnson grass not be allowed to go to seed, and that these should be inventoried and control programs implemented. MD-SHA works to meet requirement of the laws.

Question 4: What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?

Timing related. Sometimes control is not carried out on time to stop thistles from going to seed.

Question 5: How do you measure the cost effectiveness of your weed management system?

Cost effectiveness has not been conducted in the recent past.

US Fish and Wildlife Services

Contact: Chris Kane
Position: Refuge Operations Specialist (Minnesota Valley)

Kane's office is responsible for wetlands in fourteen counties within Twin cities Metro and south of the metro, comprising of over 20,000 acres of federal land.

Question 1: What methods/techniques do you use in conducting weed inventory surveys of land under your agency's management?

GIS/GPS technology is being used. Because the size of the concerned area is not too large (about 20,000 acres), general locations of specific problem weed species are known. To survey and map these infestations, sampling sites are randomly selected (no elaborate designs used). Field personnel visit the selected sites and map the infestation patches by walking them with GPS units. For large area infestations, transects are employed.

Question 2: What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?

Generally, mechanical, biological and chemical methods are utilized in weed control. They try mostly to use an integrated approach in weed management. Canada thistle is mostly mowed; however, depending on location, size and density of infestation, a combination of mowing and chemical applications are employed for effective control.

Question 3: What criteria do you use to select the most appropriate method to manage these weeds?

Effectiveness is the main criteria used in selection of management method.

Question 4: What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?

Timing and labor constraints for the size of area involved is the main constraint. (often sub-contracts Minnesota Conservation Corps to assist, and have done a great job at control).

Question 5: How do you measure the cost effectiveness of your weed management system?

There is no cost effective analysis being conducted. Currently, the department is more concerned with determining effectiveness of control measures. However, there is an apparent shift away from use of chemicals due to the high cost.

New Hampshire DOT (NH/DOT)

Contact: Marc Laurin
Position: Sr. Environmental Manager, Bureau of Environment

The office of Senior Environmental Manager is concerned with wetland mitigation and monitoring sites with invasive weed species, mostly purple loosestrife. Some biological control activities are carried out by the unit for management of purple loosestrife. Mr. Laurin referred me to head of highway maintenance (Mike Pillsbury – Tel. 603-271-2693) for questions on management activities all weeds.

Question 1: What methods/techniques do you use in conducting weed inventory surveys of land under your agency's management?

This unit of NH/DOT monitors invasive species. Purple loosestrife has been weed of concern.

Question 2: What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?

Release beetles for control of purple loosestrife in wetland mitigation areas. Some chemical application also adopted; lowering soil level to allow water to come into area.

Question 3: What criteria do you use to select the most appropriate method to manage these weeds?

Biocontrol is being used because grant money has been provided for its adoption in wetland mitigation areas.

Question 4: What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?

This unit is not involved in routine weed management activities; no specific problems stand out.

Question 5: How do you measure the cost effectiveness of your weed management system?

Cost effectiveness of control measures in not conducted.

Wyoming DOT (WY/DOT)

Contact: John Samson
Position: State Agronomist

Wyoming Department of Transportation has approximately seven thousand (7,000) miles of roads under its management. Most of the area is in the arid and semi-arid type of climate. This area also experience periods of strong winds. Herbicides need moisture to act effectively; hence local climatic conditions often discourage use of herbicides for weed management.

Question 1: What methods/techniques do you use in conducting weed inventory surveys of land under your agency's management?

WY/DOT is contracted to do weed survey for the state. The Department works in cooperation with local county weed districts in conducting the surveys. The surveys are usually visual inspections, aided by plant maps and to a minor extent with GPS technology (to date less than 25 percent of the 23 counties have been surveyed using GPS units).

Question 2: What methods are you utilizing for the control of specific (Canada thistle, leafy spurge, poison ivy) weeds?

Integrated approach is adopted in control of weeds. Chemical treatment is used as first line of defense, and is often spot applied using 4-wheelers. Mowing is also done annually in shoulder and the fore slope (usually less than twenty feet).

Question 3: What criteria do you use to select the most appropriate method to manage these weeds?

Because area to be treated is large (7,000 miles), cost of control measures is a major concern. The arid and semi-arid local climate often influences against selection of chemical measures.

Question 4: What are the primary problems that you have encountered during the application of any of the (mechanical, chemical, biological) control measures?

Wind may at times blow continuously over many days. Spraying during these windy days is not possible due to unacceptable levels of drift of herbicides. Postponement of these operations is a serious problem as timing of application of weed control measures is critical. Equipment breakdowns sometimes affect mowing operations.

Question 5: How do you measure the cost effectiveness of your weed management system?

Cost effectiveness of control measures are not routinely done. The Department has been using herbicide treatment for the last twelve (12) years; cost of use of herbicides has generally been on lower side.

Montana State

Contact: Justun Juelfs
Position: Roadside and Winter Maintenance Specialist

Background

The Montana Department of Transportation has roughly 160,000 acres of Right of Way to manage for noxious weed control. To accomplish this we have an annual budget of 1.3 million dollars. That equates to about $8 per acre, so prioritizing our weed control efforts is of the utmost importance.

Historically we have relied on the counties assistance for noxious weed control. This may happen in several ways:
Counties control weeds and we (MDT) compensate them for their efforts
Counties may contract through a third party for noxious weed control where the county would administer the contract and we would compensate them for their efforts.
This is the case for most of the State; however we have four out of fifty-six counties in the state where we control noxious weeds with state forces. This has just started to take place over the last several years. MDT is starting to take a more active role in noxious weed control.

Response to questions:

1. MDT has spent the last several years inventorying our Rights of Way for state listed noxious weeds. This started in 2003 with my predecessor. We offered to pay the individual counties $2 per lane mile for completing the inventory. At the time the inventory was taking place there were 23 weed species on the state noxious weed list. MDTs' approach was to inventory every mile of highway (12,000 miles) for the following.
Location
Weed Species
Infestation level
After the first two years we had approximately half of the counties inventoried. Then with the help of Montana State University, MDT hired a team of two individuals to complete the remaining

inventory. This took an additional two years to complete. The information has been tracked in Excel and converted to shape files for mapping purposes.

2. We use a variety of control methods including.
Herbicide Management
Biological Management
Manual and Mechanical Management
The majority (90%) of the annual budget is allocated toward herbicide management and distributed to the counties within the state.

Biological control efforts are administered when a proper location has been identified. MDT also partially funds ten High Schools within the state to develop insectaries and release the insects on MDT Rights of Way. This program has been very well received. It fits well with MDT's integrated approach and is a great platform for education and awareness.

Mechanical efforts are made in conjunction with the overall vegetation management plan goals. At times safety of the road users may come into play, for example limited sight distances. When safety is in question that takes priority over all else.

3. MDT has broken its Rights-of-Way into three separate management zones.
Zone one is considered the operational zone and is identified as starting at the pavement edge and extending out 15 feet. This has been identified as the highest priority due to the potential to spread of noxious weeds along the roadway.
Zone two is considered the transitional zone and is identified as starting 15 feet from the edge of the road to the Right-of-Way fence-line. This area is managed depending on the adjacent land owner. If the adjacent land owner has an active weed management plan it is important to be a good neighbor and control the noxious weed so we don't seed them up. If they do not have an active plan then that area may lend itself well to a bio-control release but would not take precedent over zone one.
Zone three includes our facilities, stockpile and structures. It is important for MDT to stay active in these areas. There is high potential to spread noxious weeds from our stockpiles during our winter maintenance practices. Hand pulling has been reserved for these areas.
The state weed list has also been broken into three categories.
Category one has 14 weed species, with over 8,000,000 acres infested state wide.
Category two has eight weed species, with a little over 100,000 acres infested state wide
Category three has five weed species, with less than 800 acres infested state wide.
Although category one has the most weeds, these weeds are, however, our lowest priority. At most we can hope to limit seed production and limit future spread. Category two, we may be able to win the battle. Although category three has less than 600 (800?) acres; these weeds are considered the highest priority for control. With early detection and rapid response we hope to be able to eradicate them.

4. I cannot think of anything out of the ordinary when it comes to problems with our application efforts. We have had several issues of non-target damage. In the future we may have to negotiate a no spray agreement for those whose wish not to have synthetic herbicide on the Right-of-Way that borders their property; Organic farming and ranching comes to mind.

5. We have the ability to compare "dollars" from county to county. When we meet with the counties we ask for cost per acre prices. When something seems outside of the typical cost we can then dig deeper to determine justification. With an active inventory program we will be able to measure the effectiveness through increased or decreased infestation level.

Table 1.1: List of Contacts

NAME OF ONTACT	POSITION	AFFILIATION	CONTACT INFORMATION: TELEPHONE:	EMAIL:
Augustine, Ralph		US Army Corps of Engineers	651-290-5378	
Chandler, Monika	Research Scientist (Bio-control)	Research Scientist, Bio-control, Sustainable Agriculture and IPM MDA	651-201-6468	Monika.Chandler@state.mn.us
Cober, Don	Team Lead, Technical Services.	Maryland State Highway Administration (Landscape Operations Division)	410-545-8596	dcober@sha.state.md.us
Cortilet, Anthony	Plant Health Specialist	Research Scientist, Bio-control, Sustainable Agriculture and IPM, MDA	651-282-6808	Anthony.cortilet@state.mn.us
Graddick, Collie	Pesticide & Fertilizer Management Division	Agronomy and Plant Protection, MDA	651-201-6234	Collie.Graddick@state.mn.us
Hanks, Mary	Supervisor	Research Scientist, Bio-control, Sustainable Agriculture and IPM, MDA	651-282-6808	mary.hanks@state.mn.us
Hop, Kevin	Team Leader	Vegetation Mapping Project, Upper Midwest Environ'l Siences Center (UMESC), USGS	608-781-6385	khop@usgs.gov
Jacobson, Tom		MN/DOT, District 1	218.723.4960 x3540	Tom.jacobson@dot.state.mn.us
Juelfs,Justun	Roadside and Winter Maintenance Specialist	Montana DOT	406-444-7604	jjuelfs@mt.gov
Kane, Chris	Refuge Ops. Specialist	US Fish & Wildlife, Minnesota Valley	952.858. 0703	-
Laurin, Marc	Sr. Environ. Manager	Bureau of Environment, NH/DOT	603-271-4044	-
McDill, Terry	Chair	MN Invasive Species Advisory Council, MISAC	651-297-4981	Teresa.McDill@state.mn.us

Table 1.1: List of Contacts (Cont.…)

Rendal, Jay		Minnesota Department of Natural Resources (DNR)	-	-
Samson, John	State Agronomist	Wyoming DOT	307-777-4416	jsamso@dot.state.wy.us
Skinner, Luke	Research Scientist,	Invasive Species Program, Minnesota Department of Natural Resources (DNR)	651-297-3763	Luke.skinner@dnr.state.mn.us
Walsh, Jeff		US Bureau of Land Management	703-440-1668	-
Walvatne, Paul	Forestry Unit Supervisor	MN Dept. of Transportation	651-284-3793	Paul.walvatne@dot.state.mn.us

Chapter 2

Summary Report on Preliminary Recommendations for the Required Minimum Sampling

2.1 Introduction

This chapter presents descriptions of weed survey methods, as well as results of the analysis of weed infestation data recorded in the project's surveys conducted in the summers of 2004 and 2005. The surveys adopted two sampling designs. One of the designs, referred to as the Current Mn/DOT design, has been used by Mn/DOT in its surveys within District 4 starting 2000.In this design, a sample comprising seven, 3 mile segments from highways rights-of-way, were adopted in the surveys. Questions regarding the validity of this sample to provide a representation of the whole Mn/DOT District 4 have been raised. The current project was proposed and conducted to evaluate statistical validity of this sampling design. A new sampling design was developed and adopted in surveys for infestation by select weed species in District 4, termed the New Model.

In this chapter, we have offered descriptions on procedures adopted in selection of sampling points, data recording and analysis, as well as presentation of some of the pertinent findings. Comparisons between data obtained using both sampling designs have been made, and results are presented.

The chapter is a report submitted in fulfillment of Task 3 requirements of the project.

2.2 Current Mn/DOT Sampling Design

The District 4 of Mn/DOT has been conducting and recording information on weed infestation along ROWs of the highways under its management since 2000. Since conducting an inventory of infestation in the entire District area would be both expensive and require substantial resources, a small sample size, representing approximately one percent (1%) of its entire ROWs area, has been used in the surveys. The sample comprises of seven, fixed three-mile long segments (Table 2.1). Selection of the sample was carried out following criteria as described by the District 4 maintenance unit (Supervisor, personal communication, 2004). Some of the objectives of selection criteria were to ensure that diverse conditions in the District were represented in the selected sample. The following characteristics were considered important in the selection of the ROW sampling sections.

- Road location: Urban or Rural
- Road vegetation: Wooded or non-wooded areas
- Road orientation, North-to-South or East-to-West

Table 2.1: Survey sample segments selected in District 4 (2000-04 survey design)

Segment ID	Road Name	Mile Marker range	ROWs Miles
40	MN59	231-234	6
41	US75	191-194	6
42	MN55	21-24	6
43	MN235	2-5	6
44	MN29	83-86	6
45	I-94	111-114	9
46	MN27	66-69	6

In the surveys using the Current Design, weed infestation and distribution data was collected and recorded with Trimble ProXR® Global Positioning System (GPS). The detail and extent of recorded information was guided by the data dictionary developed for the project and loaded in the GPS units. The data dictionary availed a pull-down menu which guided the operator to select/input pertinent information about the site being surveyed. This information included weed species name, percent cover, weed patch location in the landscape, adjacent land use, management obstacles, and also details on chemical spraying and other weed management operations. The use of GPS units loaded with the data dictionary was necessary to facilitate uniformity in data collection as well as minimizing recording errors by multiple operators.

2.3 New Sampling Design

The new design was constructed following procedures for design of random sampling for ecological models. The new design has been purposely adopted to collect data which would be analyzed with standard statistical tools and procedures ordinarily applied to ecological data. The model has been designed to improve on sampling intensity which is lacking in the current Mn/DOT model. This has been achieved through selection of a significantly larger sample size, randomly selected from all possible mile segments in the entire ROWs area of Mn/DOT District 4, without regard to sub-divisions (such as ecological zones, or management sub-districts) in the area (Figure 2.1). Selection of sampling sites in 2004 for the new design involved tabulating mile marker points, with a spacing of 0.25 miles, for all road miles under Mn/DOT management in District 4. From this population, a sample of 105 segments, each 0.25 mile long, were randomly selected. In the initial selection of sampling sites, the longer roads with a higher number of mile marker points had greater representation in the overall list of sampling site, while shorter roads had little or no representation in the list. Further, the initial list of sites showed a poor distribution over the District, with some large sections of the study area completely void of any sampling sites. This necessitated selection of additional points to “fill in the gaps” in unrepresented areas in the District. This increased the total number of selected sampling sites to 120.

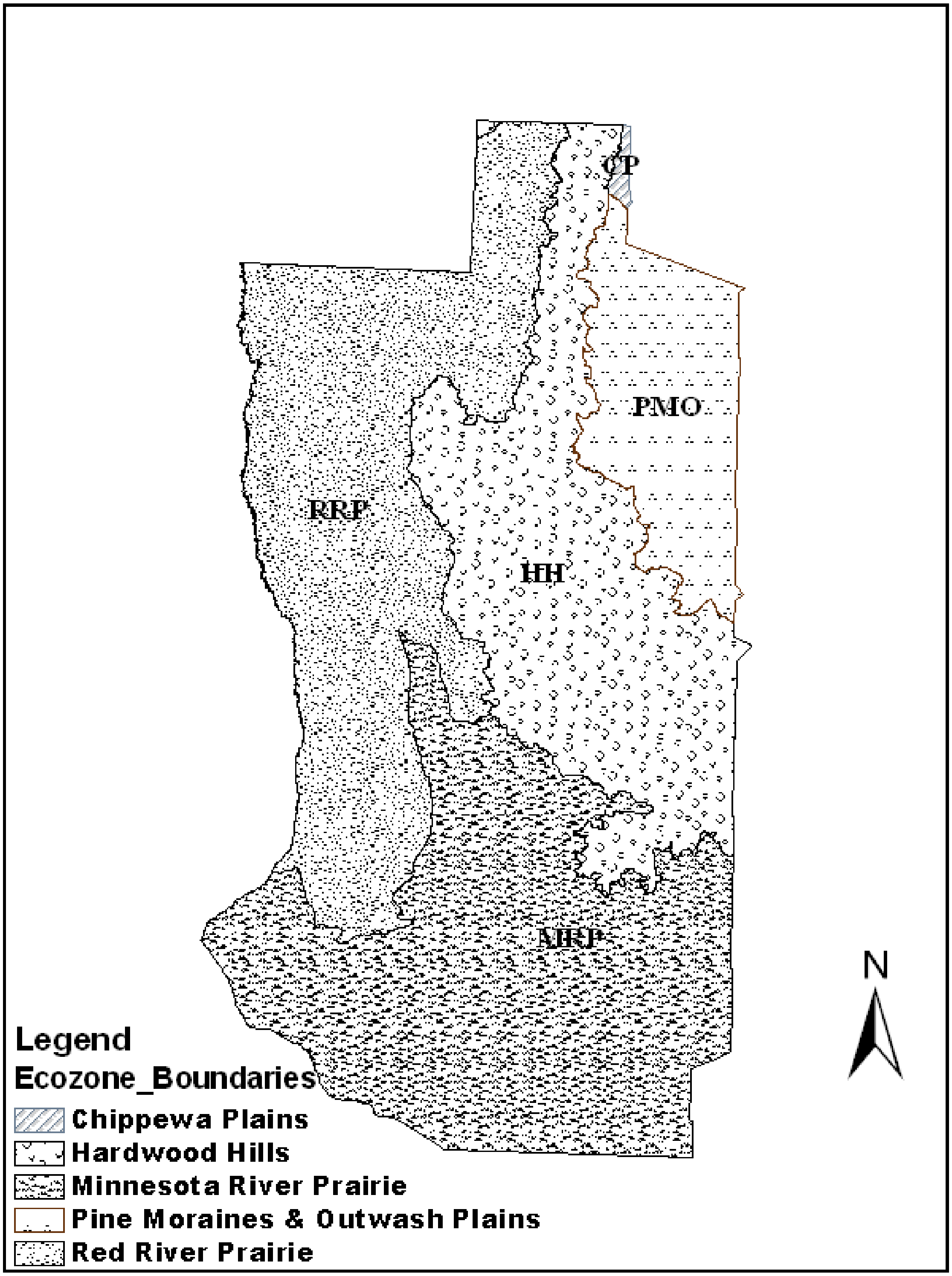


Figure 2.1a: Ecological Zones of the study area (Mn/DOT District 4)

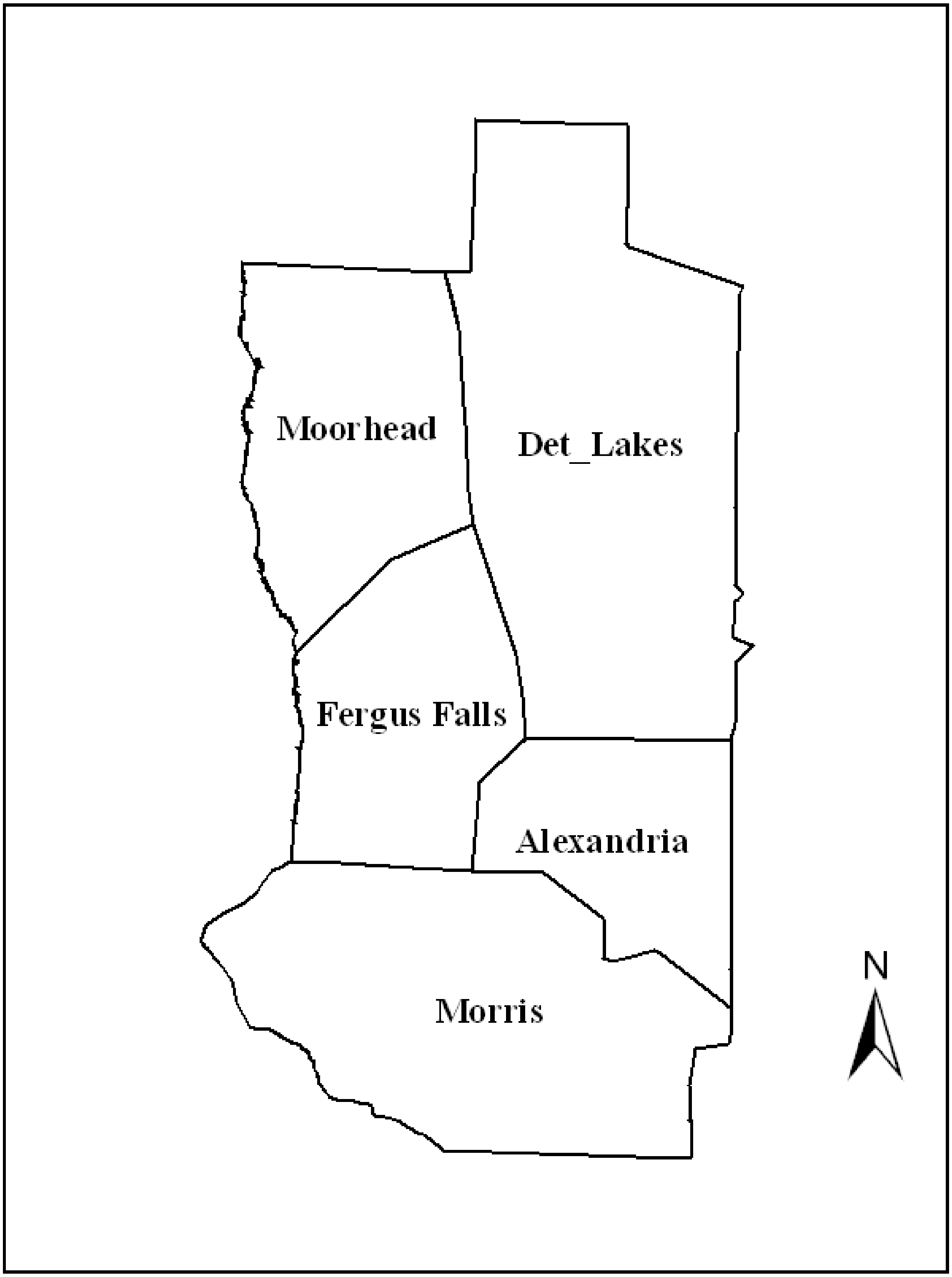


Figure 2.1b: Management sub-districts of the study area (Mn/DOT District 4)

Table 2.2: Sampling sites selected (completely randomized) for surveys conducted in 2004, Mn/DOT District 4

Subdistrict	SegmentID	No. of Sites	Linear Miles	Road EdgeMile
Alexandria	114_15.5	1	0.25	0.5
	114_6.75	1	0.25	0.5
	27_92	1	0.25	0.5
	28_83.25	1	0.25	0.5
	28_83.5	1	0.25	0.5
	29_91	1	0.25	0.5
	55_36.5	1	0.25	0.5
	55_39.75	1	0.25	0.5
	55_40.25	1	0.25	0.5
	55_42.5	1	0.25	0.5
	55_54.5	1	0.25	0.5
	55_74.75	1	0.25	0.5
	94_107.5	1	0.25	0.75
	94_84.75	1	0.25	0.75
	94_87.5	1	0.25	0.75
	94_92	1	0.25	0.75
	94_93.75	1	0.25	0.75
Alexandria Total		**17**	**4.25**	**9.75**
Det_Lakes	10_39.75	1	0.25	0.75
	10_77	1	0.25	0.75
	10_78.25	1	0.25	0.75
	10_80	1	0.25	0.75
	106_4.25	1	0.25	0.5
	108_53	1	0.25	0.5
	113_29.5	1	0.25	0.5
	113_42.5	1	0.25	0.5
	113_43.75	1	0.25	0.5
	113_50.75	1	0.25	0.5
	113_53.25	1	0.25	0.5
	113_9.75	1	0.25	0.5
	200_62.25	1	0.25	0.5
	210_53	1	0.25	0.5
	224_1	1	0.25	0.5
	29_111.5	1	0.25	0.5
	29_118.25	1	0.25	0.5
	34_48.25	1	0.25	0.5
	34_53.25	1	0.25	0.5
	34_58	1	0.25	0.5
	78_13.25	1	0.25	0.5
	78_37.25	1	0.25	0.5
	78_7.75	1	0.25	0.5
Det_Lakes Total		**23**	**5.75**	**12.5**

Subdistrict	nentID	No. of Sites	Linear Miles	Road EdgeMile
Fergus Falls	210_18.75	1	0.25	0.5
	210_9.75	1	0.25	0.5
	27_26	1	0.25	0.5
	27_37.5	1	0.25	0.5
	54_8	1	0.25	0.5
	55_0.25	1	0.25	0.5
	55_0.5	1	0.25	0.5
	55_7.5	1	0.25	0.5
	75_176.25	1	0.25	0.5
	75_177.5	1	0.25	0.5
	75_184.5	1	0.25	0.5
	75_190.5	1	0.25	0.5
	9_105.25	1	0.25	0.5
	9_92	1	0.25	0.5
	94_59.75	1	0.25	0.75
	94_63.75	1	0.25	0.75
	94_66.5	1	0.25	0.75
	94_70	1	0.25	0.75
	94_72	1	0.25	0.75
	94_74	1	0.25	0.75
Fergus Falls Total		**20**	**5**	**11.5**
Moorhead	10_27	1	0.25	0.75
	10_29.5	1	0.25	0.75
	32_25.25	1	0.25	0.5
	34_11.75	1	0.25	0.5
	34_13	2	0.25	0.5
	34_14.75	1	0.25	0.5
	34_6	1	0.25	0.5
	75_213.25	1	0.25	0.5
	75_214	1	0.25	0.5
	75_220.25	1	0.25	0.5
	75_237.5	1	0.25	0.5
	75_257	1	0.25	0.5
	9_135.25	1	0.25	0.5
	9_139.5	1	0.25	0.5
	9_163.25	1	0.25	0.5
	9_167.75	1	0.25	0.5
	9_170.25	1	0.25	0.5
	9_174	1	0.25	0.5
	9_179.5	1	0.25	0.5
	94_20	1	0.25	0.75
	94_30.75	1	0.25	0.75
	94_8	1	0.25	0.75
Moorhead Total		**23**	**5.5**	**12.25**

Table 2.2: Sampling sites selected (completely randomized) for surveys conducted in 2004, Mn/DOT District 4 (cont….)

Subdistrict	SegmentID	No. of Sites	Linear Miles	Road Edge Miles
Morris	104_19.75	1	0.25	0.5
	104_32.75	1	0.25	0.5
	119_12.25	1	0.25	0.5
	119_6.5	1	0.25	0.5
	27_19.25	1	0.25	0.5
	28_12.5	1	0.25	0.5
	28_19.75	1	0.25	0.5
	28_23.75	1	0.25	0.5
	28_33.25	1	0.25	0.5
	28_36.5	1	0.25	0.5
	28_42	1	0.25	0.5
	28_64.75	1	0.25	0.5
	29_27	1	0.25	0.5
	29_35.75	1	0.25	0.5
	7_1	1	0.25	0.5
	7_1.25	1	0.25	0.5
Morris Total		**16**	**4**	**8**
District 4 Grand Total		**99**	**24.5**	**54**

* Road-edge-miles is the length of a section of highway multiplied by number of road edges in the section; one mile section of a divided highway is 3 road edge miles (1 x 3 road edges i.e., left and right edges, and the median)

The New Sampling Design, together with the Current Mn/DOT Design (3-mile segments) , were adopted in surveys conducted during the 2004 season. The obtained data sets were adopted in attempts to validate statistical validity of the 3-mile survey design. In order to evaluate statistical validity of the sampling intensity of the current Mn/DOT model, data analysis involved evaluation of means and their application in testing differences among the two designs.

The final list of selected quarter-mile sampling sites for the 2004 surveys is presented in Table 2.2.

2.4 2005 Surveys

Lessons from selection of samples during the 2004 survey season were applied to improving selection for surveys in 2005. The issue of poor sample distribution experienced in adopting complete random selection over the whole study area, was improved upon by stratification. The population of mile marker points in Mn/DOT managed highways in the study area (Mn/DOT District 4) were identified based on ecological zones they are located in (Figure 2.1). A sub-sample was randomly selected from these locations in an ecological zone. The number selected for each zone was proportional to total Mn/DOT highway managed highway miles in the zone. A total of 120 sites were selected from District 4, which were adopted for surveys.

Field surveys were conducted during the months of June to early August. During the 2005 season, problems arising from deadlocks in budget debates in state government (ending with State government shut-down) resulted in a delay to completion of field surveys (scheduled to coincide with survey dates for 2004 season). Table 2.3 is a comprehensive list of the 120 sites selected for sampling. Further, during field surveys, other problems were encountered which resulted in survey and data recording not being conducted at some of these selected sites. These problems included:

- sampling sites located within townships (where highways ROWs are always clean mowed)
- some sampling points were located in terrain too dangerous to access, or along sections of roads currently under repair and/or construction
- heavy rains caused flooding in some regions, hence were inaccessible

The comments column in Table 2.3 explains reasons for a site having not been surveyed.

2.5 Data Processing and Analysis

The acquired raw data files in the GPS data logger were uploaded onto computers in the Water Resources Modeling Laboratory (Department of Biosystems and Agricultural Engineering - University of Minnesota), and pre-processed in the GPS Pathfinder Office® (vs. 3.0) software environment. Preprocessing involved subjecting the data to differential correction for improved positional accuracy, previewing and removal of errors. These files were then exported as shapefiles for display and further processing in the GIS (ArcView/ArcMap) environment.

Table 2.3: Sampling sites selected (stratified by ecological zones, then completely randomized) for surveys conducted in 2005, Mn/DOT District 4

Ecological Zone	Segment ID	Road Edge Surveyed (miles)	Sub-district	Comments on Surveys status of Individual sites++
Chippewa Plains	MN200_66	0.50	Det_Lakes	Y
Hardwood Hills	MN108_17	0.50	Det_Lakes	Missed
	MN29_115	0.50	Det_Lakes	Site Flooded
	I94_95.75	0.75	Alexandria	Y
	I94_106	0.75	Alexandria	Y
	MN108_31	0.50	Det_Lakes	Y
	MN108_32	0.50	Det_Lakes	Y
	MN108_33.25	0.50	Det_Lakes	Y
	MN200_58.75	0.50	Det_Lakes	Y
	MN210_34.25	0.50	Fergus Falls	Y
	MN210_77.25	0.50	Det_Lakes	Y
	MN29_96	0.50	Alexandria	Y
	MN29_110.75	0.50	Det_Lakes	Y
	MN78_8.25	0.50	Det_Lakes	Y
	MN78_14.5	0.50	Det_Lakes	Y
	MN78_18.5	0.50	Det_Lakes	Y
	US10_27.5	0.75	Moorhead	Y
	US10_58.25	0.75	Det_Lakes	Y
	US10_61.25	0.75	Det_Lakes	Y
	US59_237.75	0.50	Fergus Falls	Y
	US59_256.5	0.50	Det_Lakes	Y
	US59_262	0.50	Det_Lakes	Y
	US59_265.25	0.50	Det_Lakes	Y
	MN78_46.5	0.50	Det_Lakes	Y (mowed clean)
Minnesota R. Prairie	I94_77	0.75	Alexandria	Site Construction
	I94_78	0.75	Alexandria	Site Construction
	MN7_15	0.50	Morris	Dangerous terrain
	MN28_8.5	0.50	Morris	In Town
	MN28_47.5	0.50	Morris	In Town
	MN29_53.75	0.50	Morris	In Town
	MN55_70	0.50	Alexandria	In Town
	MN55_32	0.50	Alexandria	Site Flooded

++ Key: Y = site was surveyed; N = site not surveyed; Missed = not surveyed, no reason indicated

Table 2.3: Sampling sites selected (stratified by ecological zones, then completely randomized) for surveys conducted in 2005, Mn/DOT District 4 (cont….)

Ecological Zone	Segment ID	Road Edge Surveyed (miles)	Sub-district	Comments on Surveys status of Individual sites
Minnesota R. Prairie	I94_105.25	0.75	Alexandria	Y
	I94_105.5	0.75	Alexandria	Y
	I94_105.75	0.75	Alexandria	Y
	MN114_1.5	0.50	Alexandria	Y
	MN27_40	0.50	Fergus Falls	Y
	MN27_88	0.50	Alexandria	Y
	MN27_88.25	0.50	Alexandria	Y
	MN28_23.75	0.50	Morris	Y
	MN28_42.5	0.50	Morris	Y
	MN28_51.75	0.50	Morris	Y
	MN28_52	0.50	Morris	Y
	MN29_23.25	0.50	Morris	Y
	MN29_28.5	0.50	Morris	Y
	MN29_29	0.50	Morris	Y
	MN29_53.25	0.50	Morris	Y
	MN55_73.75	0.50	Alexandria	Y
	MN55_75	0.50	Alexandria	Y
	MN55_75.25	0.50	Alexandria	Y
	MN7_22.75	0.50	Morris	Y
	MN7_52.25	0.50	Morris	Y
	MN79_11.25	0.50	Alexandria	Y
	MN9_33.25	0.50	Morris	Y
	MN9_46.75	0.50	Morris	Y
	MN9_52.75	0.50	Morris	Y
	MN9_54.75	0.50	Morris	Y
	US12_8	0.50	Morris	Y
	US12_8.75	0.50	Morris	Y
	US12_12.5	0.50	Morris	Y
	US12_16.5	0.50	Morris	Y
	US12_17	0.50	Morris	Y
	US12_26.25	0.50	Morris	Y
	US12_39.25	0.50	Morris	Y
	US12_40	0.50	Morris	Y
	US12_40.25	0.50	Morris	Y

Table 2.3: Sampling sites selected (Stratified by ecological zones, then completely randomized) for surveys conducted in 2005, Mn/DOT District 4 (cont….)

Ecological Zone	Segment ID	Road Edge Surveyed (miles)	Sub-district	Comments on Surveys status of Individual sites
Minnesota R. Prairie	US59_147.75	0.50	Morris	Y
	US59_152.75	0.50	Morris	Y
	US59_177.25	0.50	Morris	Y
	US75_129	0.50	Morris	Y
	US75_136.25	0.50	Morris	Y
	US75_151.5	0.50	Morris	Y
	US75_160.75	0.50	Morris	Y
	US75_148	0.50	Morris	Y (mowed clean)
Pine Moraines	MN225_1.75	0.50	Det_Lakes	DUPLICATE
	MN87_20.25	0.50	Det_Lakes	DUPLICATE
	MN87_11.5	0.50	Det_Lakes	Missed
	MN87_11.5	0.50	Det_Lakes	Missed
	MN225_0.25	0.50	Det_Lakes	In Town
	MN225_1.75	0.50	Det_Lakes	Y
	MN34_58	0.50	Det_Lakes	Y
	MN34_63.5	0.50	Det_Lakes	Y
	MN34_63.75	0.50	Det_Lakes	Y
	MN87_11.75	0.50	Det_Lakes	Y
	MN87_20.25	0.50	Det_Lakes	Y
Red River Prairie	I94_10.25	0.75	Moorhead	Site Construction
	US59_299.75	0.50	Det_Lakes	In Town
	MN55_11.25	0.50	Fergus Falls	Site Flooded
	US75_196	0.50	Fergus Falls	Site Flooded
	US75_200.25	0.50	Fergus Falls	Site Flooded
	I94_24.75	0.75	Moorhead	Y
	I94_28.75	0.75	Moorhead	Y
	I94_30	0.75	Moorhead	Y
	MN210_11.25	0.50	Fergus Falls	Y
	MN224_4	0.35	Det_Lakes	Y
	MN27_29.75	0.50	Fergus Falls	Y

Table 2.3: Sampling sites selected (Stratified by ecological zones, then completely randomized) for surveys conducted in 2005, Mn/DOT District 4 (cont….)

Ecological Zone	Segment ID	Road Edge Surveyed (miles)	Sub-district	Comments on Surveys status of Individual sites
Red River Prairie	MN27_33.75	0.50	Fergus Falls	Y
	MN27_34.5	0.50	Fergus Falls	Y
	MN32_0.25	0.50	Moorhead	Y
	MN32_34.25	0.50	Moorhead	Y
	MN34_2.25	0.50	Moorhead	Y
	MN9_137.75	0.50	Moorhead	Y
	MN9_140.5	0.50	Moorhead	Y
	MN9_141.75	0.50	Moorhead	Y
	MN9_163	0.50	Moorhead	Y
	MN9_164.25	0.50	Moorhead	Y
	MN9_168.75	0.50	Moorhead	Y
	US10_19.75	0.75	Moorhead	Y
	US59_228.5	0.50	Fergus Falls	Y
	US59_236.25	0.50	Fergus Falls	Y
	US59_269.5	0.50	Det_Lakes	Y
	US59_296.75	0.50	Det_Lakes	Y
	US59_303.25	0.50	Det_Lakes	Y
	US59_311.75	0.50	Det_Lakes	Y
	US75_171	0.18	Fergus Falls	y
	US75_173.75	0.50	Fergus Falls	Y
	US75_178.5	0.50	Fergus Falls	Y
	US75_180.75	0.50	Fergus Falls	Y
	US75_220.75	0.50	Moorhead	Y
	US75_240	0.50	Moorhead	Y
	US75_245.75	0.50	Moorhead	Y
	US75_263.25	0.50	Moorhead	Y

Ecological data for the study area was downloaded from the DNR Data Deli (http://maps.dnr.state.mn.us/deli/). This spatial data layer was inserted into the ArcMap/ArcView® GIS software, where it was reclassified into five natural classes of the major ecological zones in the District. Two spatial data layers of the weed inventory (shapefiles exported from GPS Pathfinder) collected following the procedures described above, were also inserted and overlaid with two other spatial data layers (classified ecological zones, and mile markers points layers) for the study area. Spatial data layers were created and saved for each of the ecological classes by onscreen digitizing along zone boundaries. Using the ArcMap Geoprocessing tools, the ecological class layer was subjected to intersection analysis with each of the spatial data layers of mile marker points and weed inventory. Four shapefiles were generated in the intersections; these are defined as:

- Ecological zones with mile marker points – survey procedure 1 (milemarkers_3mile_segment.shp)
- Ecological zones with mile marker points - survey procedure 2 (milemarkers_1/4mile_segment.shp)
- Ecological zones with weed inventory data - survey procedure 1 (weeds_3mile_segment.shp)
- Ecological zones with weed inventory data - survey procedure 2 (weeds_1/4mile_segment.shp)

Attribute data tables for each of these layers were exported for further processing in a Microsoft Excel® spreadsheet.

2.6 Determination of Area and Mean Infestations

To evaluate statistical validity of the current survey procedures adopted by Mn/DOT, a comparison of select parameters would be necessary. One such parameter is mean weed infestation in the highways ROW. Values for this parameter will be evaluated from the two data sets obtained following the current survey procedures and the survey procedures developed in this study.

The two databases from intersection of road mile marker points and ecological zones were sorted by ecological class name and highway names. Highways were further classified depending on whether it was a ‘divided’ or ‘undivided highway’. Total miles of highway rights-of-way (ROWs) were determined for each road using Equation 1 below.

The exported databases from the intersection analysis of weed inventory and ecological zones spatial data were opened in the MS Excel® spreadsheet, and sorted by ecological class name, weed species, and percent infestation. Total area infested by each of the three weed species, at different percent cover classes, were computed using Equation 2 for each ecological zone. Mean infestation (acres per linear mile), variance and standard deviations were also determined using Equations 3, 4 and 5 below.

The obtained values from our calculations on the data collected in the 2004-05 seasons following the two survey sampling designs are summarized in Tables 2.4 – 2.7.

Total miles of road rights-of-way surveyed per ecological zone is:
(Tmiles) = Sum of the product (length of each sampled segment, number of segments in the highway, number of road sides/edges [2 or 3])

$$\text{Tmiles} = \sum_{j=0}^{m} \sum_{i=0}^{n} Sij.N.L \quad \text{.. (1)}$$

where

m = total number of highways surveyed in a given ecological zone of District 4,
n = total number of segments surveyed along a highway in an ecological zone,
Sij = the ith segment of the jth highway in an ecological zone
N = number of sides/edges of highway (3 for 'divided highway', 2 for 'undivided')
L = Length of segment (3 for 3-mile, or 0.25 for 1/4 mile segments)

2.6.1. Total weed Infestation area

The total area infested per ecological zone was calculated by summing up the areas of individual patches surveyed for each of the three weed species (Canada thistle, poison ivy, and leafy spurge), and the totals for the zones summed to yield total for the study area. When necessary, the areas for different infestation densities or percent cover (10-32, 33-65 and 66-100%) were similarly determined. Figure 2.2 offers an illustration of patches of infestation by Canada thistle (labeled ct 1 – ct 5) and poison ivy (labeled p1 – p3) in one of the segments (segment i).

$$\text{Total Area for given weed species (SumWD)} = \sum_{j=0}^{m} \sum_{i=0}^{q} Pij \quad \text{...................... (2)}$$

where

q = total number of weed patches of a given infestation density mapped in a segment
Pij = area of the ith weed patch in the jth highway in the cover class.

The computation is repeated for each of the three different infestation densities. If so required, these can be summed to obtain total area infested with a given weed species, for all cover classes combined, within a District or ecological zone.

The mean infestation per mile length (Mean) for a given weed at specified density was obtained from:

$$\text{Mean} = \frac{SumWD}{Tmiles} \quad \text{.. (3)}$$

$$\text{Variance} = \frac{\sum_{i=0}^{n} (X_i - mean)^2}{(n-1)} \quad \text{.. (4)}$$

where X_i = is area of the ith described weed patch in a class
n = total number of described patches in a class

$$\text{Standard Deviation} = \sqrt{Variance} \quad \text{....................................... (5)}$$

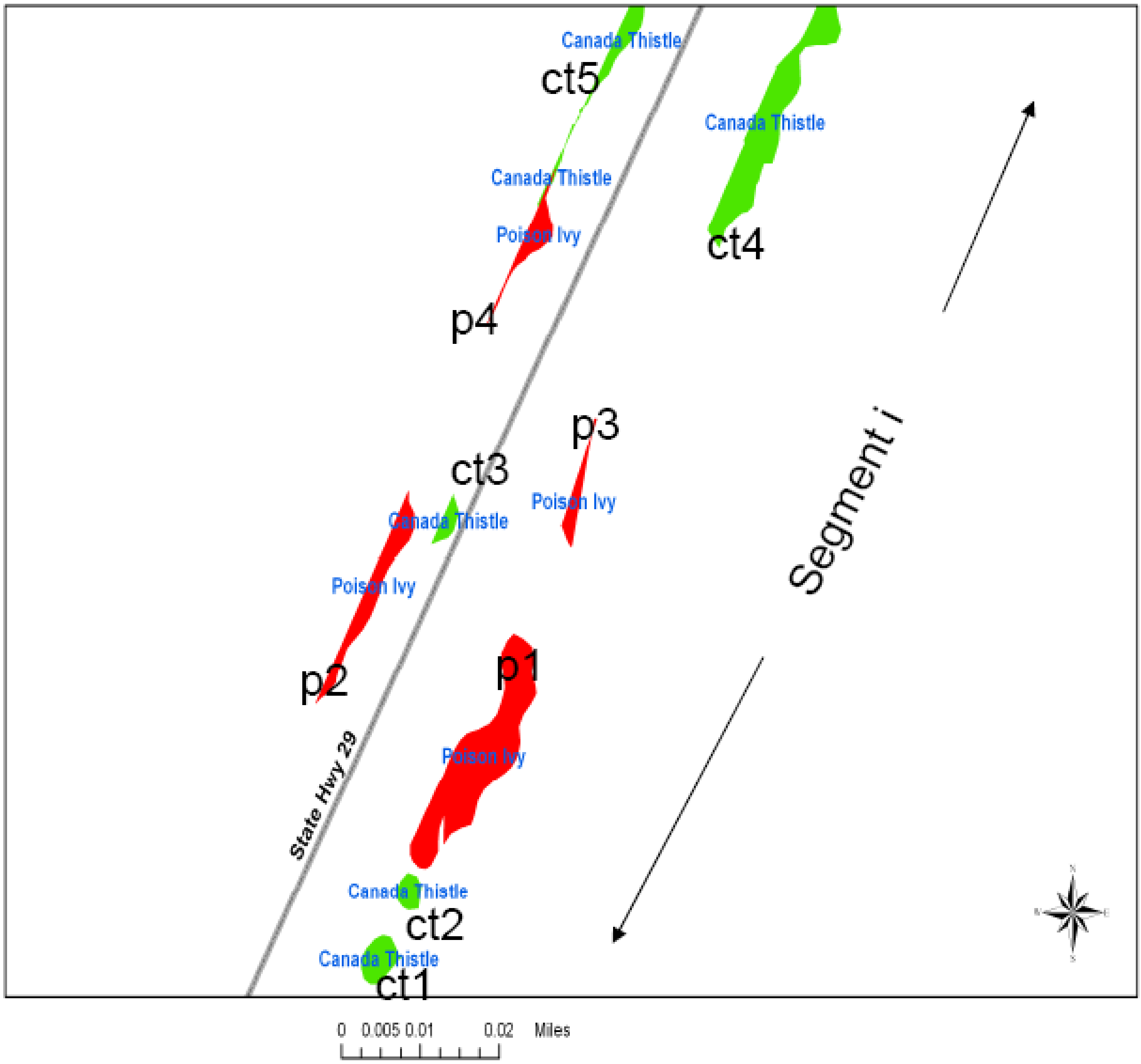


Figure 2.2: Illustration of a segment (segment i) on State highway 29 infested by Canada thistle and poison ivy with Canada thistle infestation patches (ct1 – ct5) and poison ivy patches (p1 – p4)

Table 2.4: Summary of infestations in ecological zones and management sub-districts of the study area (District 4) by Canada thistle, leafy spurge and poison ivy based on ¼-mile sampling designs, 2004

Ecological zones - Qtr mile						
Species	Ecological zone	Total Area Infested (acres)	Surveyed Area (Linear Miles)	Mean qtr-mi (acres/mile)	Weighting Factor	Grand Mean (acres/mile)
Canada thistle	Hardwood	5.675	4.000	1.419	0.215	2.079
	Minnesota	20.097	8.500	2.364	0.393	
	Pine Moraines	0.878	3.250	0.270	0.077	
	Red River	22.931	8.750	2.621	0.314	
Leafy spurge	Hardwood	0.000	4.000	0.000	0.215	0.005
	Minnesota	0.085	8.500	0.010	0.393	
	Pine Moraines	0.000	3.250	0.000	0.077	
	Red River	0.027	8.750	0.003	0.314	
Poison ivy	Hardwood	0.547	4.000	0.137	0.215	0.039
	Minnesota	0.081	8.500	0.010	0.393	
	Pine Moraines	0.265	3.250	0.082	0.077	
	Red River	0.000	8.750	0.000	0.314	

Management Sub-Districts - Qtr-mile					
Species	SubDistrict	Total Area Infested (acres)	Surveyed Area (Linear Miles)	Mean qtr-mi (acres/mile)	Grand Mean (acres/mile)
Canada thistle	Alexandria	13.668	4.500	3.037	1.787
	Det_Lakes	2.145	5.750	0.373	
	Fergus Falls	10.759	5.000	2.152	
	Moorhead	17.022	5.500	3.095	
	Morris	5.988	4.000	1.497	
Leafy spurge	Alexandria	0.085	4.500	0.019	0.004
	Det_Lakes	0.000	5.750	0.000	
	Fergus Falls	0.000	11.000	0.000	
	Moorhead	0.027	5.500	0.005	
	Morris	0.000	4.000	0.000	
Poison ivy	Alexandria	0.085	4.500	0.019	0.042
	Det_Lakes	0.805	5.750	0.140	
	Fergus Falls	0.000	5.000	0.000	
	Moorhead	0.004	5.500	0.001	
	Morris	0.000	4.000	0.000	

Table 2.5: Summary of infestations in ecological zones and management sub-districts of the study area (District 4) by Canada thistle, leafy spurge and poison ivy based on 3-mile sampling designs, 2004

Ecological zones - 3-mile					
Species	Ecological zone	Total Area Infested (acres)	Surveyed Area (Linear Miles)	Mean 3-mi (acres/mile)	Grand Mean (acres/mile)
Canada thistle	Hardwood	7.473	9.000	0.830	1.057
	Minnesota	7.943	6.000	1.324	
	Pine Moraines	0.000	0.000	0.000	
	Red River	6.785	6.000	1.131	
Leafy spurge	Hardwood	0.317	9.000	0.035	0.046
	Minnesota	0.534	6.000	0.089	
	Pine Moraines	0.000	0.000	0.000	
	Red River	0.118	6.000	0.020	
Poison ivy	Hardwood	2.385	9.000	0.265	0.118
	Minnesota	0.000	6.000	0.000	
	Pine Moraines	0.000	0.000	0.000	
	Red River	0.088	6.000	0.015	

Management Sub-Districts - 3-mile					
Species	SubDistrict	Total Area Infested (acres)	Surveyed Area (Linear Miles)	Mean 3-mi (acres/mile)	Grand Mean (acres/mile)
Canada thistle	Alexandria	11.903	9.000	1.323	1.057
	Det_Lakes	0.370	3.000	0.123	
	Fergus Falls	9.928	9.000	1.103	
	Moorhead	0.000	0.000	0.000	
	Morris	0.000	0.000	0.000	
Leafy spurge	Alexandria	0.293	9.000	0.033	0.046
	Det_Lakes	0.024	3.000	0.008	
	Fergus Falls	0.652	9.000	0.072	
	Moorhead	0.000	0.000	0.000	
	Morris	0.000	0.000	0.000	
Poison ivy	Alexandria	2.110	9.000	0.234	0.118
	Det_Lakes	0.274	3.000	0.091	
	Fergus Falls	0.088	9.000	0.010	
	Moorhead	0.000	0.000	0.000	
	Morris	0.000	0.000	0.000	

Table 2.6: Summary of infestations in ecological zones and management sub-districts of the study area (District 4) by Canada thistle, leafy spurge and poison ivy based on ¼-mile sampling designs, 2005

Species	Ecological Zone	Total Area Infested (acres)	Surveyed Area (Linear Miles)	Mean qtr-mile (acres/L.mile)	Weighting Factor	Grand Mean (acres/mile)
Canada Thistle	Chippewa	0.004	0.250	0.015	0.001	2.839
	Hardwood	16.403	5.328	3.079	0.215	
	Minnesota River	26.749	10.250	2.610	0.393	
	Pine Moraines	0.461	1.500	0.307	0.077	
	Red River	28.466	7.925	3.592	0.314	
Leafy Spurge	Chippewa	0.000	0.250	0.000	0.001	0.009
	Hardwood	0.144	5.328	0.027	0.215	
	Minnesota River	0.059	10.250	0.006	0.393	
	Pine Moraines	0.000	1.500	0.000	0.077	
	Red River	0.020	7.925	0.002	0.314	
Poison Ivy	Chippewa	0.000	0.250	0.000	0.001	0.163
	Hardwood	0.699	5.328	0.131	0.215	
	Minnesota River	0.320	10.250	0.031	0.393	
	Pine Moraines	2.254	1.500	1.502	0.077	
	Red River	0.151	7.925	0.019	0.314	

Species	SubDistrict	Total Area Infested (acres)	Surveyed Area (Linear Miles)	Mean qtr-mile (acres/L.mile)	Grand Mean (acres/mile)
Canada Thistle	Alexandria	10.711	3.250	3.296	2.839
	Det_Lakes	7.759	7.000	1.108	
	Fergus Falls	11.274	3.088	3.652	
	Moorhead	19.207	4.500	4.268	
	Morris	23.132	7.675	3.014	
Leafy Spurge	Alexandria	0.035	3.250	0.011	0.009
	Det_Lakes	0.144	7.000	0.021	
	Fergus Falls	0.006	3.088	0.002	
	Moorhead	0.014	4.500	0.003	
	Morris	0.024	7.675	0.003	
Poison Ivy	Alexandria	0.252	3.250	0.078	0.163
	Det_Lakes	2.637	7.000	0.377	
	Fergus Falls	0.234	3.088	0.076	
	Moorhead	0.000	4.500	0.000	
	Morris	0.301	7.675	0.039	

Table 2.7a: Summary of infestations in ecological zones of District 4 by Canada thistle, leafy spurge and poison ivy based on 3-mile sampling designs, 2005

Species	Ecological Zone	Total Area Infested (acres)	Surveyed Area (Linear Miles)	Mean 3-mile (acres/L.mile)	Grand Mean (acres/mile)
Canada Thistle	Chippewa	0.000	0.000	-	2.439
	Hardwood	9.099	9.000	1.011	
	Minnesota River	34.728	6.000	5.788	
	Pine Moraines	0.000	0.000	-	
	Red River	7.349	6.000	1.225	
Leafy Spurge	Chippewa	0.000	0.000	-	0.004
	Hardwood	0.049	9.000	0.005	
	Minnesota River	0.032	6.000	0.005	
	Pine Moraines	0.000	0.000	-	
	Red River	0.000	6.000	0.000	
Poison Ivy	Chippewa	0.000	0.000	-	0.114
	Hardwood	2.339	9.000	0.260	
	Minnesota River	0.063	6.000	0.010	
	Pine Moraines	53.658	0.000	-	
	Red River	0.000	6.000	0.000	

Table 2.7b: Summary of infestations in management sub-area of District 4 by Canada thistle, leafy spurge and poison ivy based on 3-mile sampling designs, 2005

Species	SubDistrict	Total Area Infested (acres)	Surveyed Area (Linear Miles)	Mean 3-mile (acres/L.mile)	Grand Mean (acres/mile)
Canada Thistle	Alexandria	39.983	9.000	4.443	2.439
	Det_Lakes	3.309	3.000	1.103	
	Fergus Falls	7.882	9.000	0.876	
	Moorhead	0.000	0.000	-	
	Morris	0.000	0.000	-	
Leafy Spurge	Alexandria	0.068	9.000	0.008	0.004
	Det_Lakes	0.012	3.000	0.004	
	Fergus Falls	0.000	9.000	0.000	
	Moorhead	0.000	0.000	-	
	Morris	0.000	0.000	-	
Poison Ivy	Alexandria	1.909	9.000	0.212	0.114
	Det_Lakes	0.430	3.000	0.143	
	Fergus Falls	0.063	9.000	0.007	
	Moorhead	0.000	0.000	-	
	Morris	0.000	0.000	-	

2.6.2. Comparison of means

The mean weed infestation values, as well as the results of comparison of the values from data obtained using the current Mn/DOT and new survey designs are summarized in tables 2.8 and 2.9. The results show the means of data obtained with current Mn/DOT procedures fall within one standard deviation of those obtained with the new survey procedures. However, the values from the current Mn/DOT procedures were consistently lower than the latter ones. This may be due to a higher sampling intensity (more sampling sites) adopted in the latter procedures. It is also noteworthy to point out that the current Mn/DOT survey procedures have retained the same sampling sites over the duration of the monitoring program. It is possible weed management practices have been inadvertently more effective in those particular areas due to possible bias, and as a result there might be a biased reduction in weed infestations at the sampled segments.

Table 2.8: Comparison of mean acres-per-mile for Canada thistle, leafy spurge and poison ivy infestations predicted by 3-mile and ¼-mile survey design, District 4 (2005)

Species	¼-mile (acre/L.mile)	3-mile (acre/L.mile)	df (¼-mile)	df (3-Mile)	¼-mile CI*	3-mile CI
Canada thistle	2.839a ++	2.439a	100	6	0.640	11.843
Leafy spurge	0.009a	0.004a	100	6	0.011	0.018
Poison ivy	0.163a	0.114a	100	6	0.143	0.674

++ Values with the same symbol within a row are not significantly different ($\alpha = 0.05$)
* Confidence intervals

Table 2.9: Mean acres-per-linear mile of Canada thistle, leafy spurge and poison ivy infestations by ¼-mile sampling design ecological zones of District 4 (2005 Surveys)

Species	Ecological Zone	¼-mile (acre/L.mile)	¼-mile Confidence Interval	N
Canada thistle	Overall D4	2.839b +	0.323	101
	Pine Moraines	0.307a	0.287	6
	Minnesota Prairie	2.610b	0.744	41
	Hardwood Hills	3.079b	1.751	22
	Red River	3.592b	1.364	32
Leafy spurge	Overall D4	0.009b	0.011	101
	Pine Moraines	0.000a	0.000	6
	Red River	0.002b	0.003	41
	Minnesota Prairie	0.006b	0.005	22
	Hardwood Hills	0.027c	0.052	32
Poison ivy	Overall D4	0.163a	0.143	101
	Red River	0.019a	0.039	6
	Minnesota Prairie	0.031a	0.040	41
	Hardwood Hills	0.131a	0.121	22
	Pine Moraines	1.502b	2.877	32

+ The ¼-mile means (acres-per-L.mile) for a species with the same symbols are not significantly different ($\alpha = 0.05$)

Chapter 3

Recommended Minimum Sampling Frequency

The overall objective of the project was the validation of the sampling design adopted by Mn/DOT in its weed surveys initiated in 2000. This chapter addresses the process followed in selecting sampling sites adopted in the current project during 2004 and 2005 survey seasons. This new sampling design adopting smaller size (quarter-mile long) roadway segments is reviewed within the chapter. Information on selection and implementation of the sampling design (3-mile) currently employed by Mn/DOT is also discussed. Improvements incorporated into the sampling design and data collection between 2004 and 2005 due to problems experienced in the 2004 surveys, are also highlighted.

This report was prepared and submitted in fulfillment of Task 4 of this project.

3.1 Introduction

One of the main problems encountered by weed managers is obtaining accurate information on location of problem weeds over the vast natural landscapes. In theory, this can be accomplished through conducting regular inventories in the subject ecosystems. Where infestations over given landscapes are uniform, homogeneous and contiguous, conducting required inventories may be feasible. However, in the normally large natural landscapes, infestations are rarely uniform and/or homogenous in nature. Conducting inventories over such areas would be impractical, or where attempted, will be costly and demand considerable resources. Obtaining this information may be possible through use of alternative approaches. Two commonly used approaches are: (1) sampling (surveying) smaller areas and using obtained information to extrapolate or predict infestation over the large areas, or (2) use of models to predict occurrence or potential for invasion of a given area by target weed species.

3.2 Sample Selection

Ecological sampling usually involves estimating abundance and attributes of plants in populations and communities. To obtain details on the kind of plants present in a particular habitat, plus information on the distribution and density of each species, requires that one locate and count each and every species present. This is difficult to accomplish because of the large number of plants and size of landscape involved. A way around this problem is to take a number of samples from around the habitat, then make a necessary assumption, that these samples are representative of the habitat in general. To be reasonably sure that the results obtained from the samples are as accurately representative of the habitat as possible, careful initial planning is essential (Offwell Woodland & Wildlife Trustwell). There are many different sampling methods for large natural areas. According to Rew et al (2005), there has been little work addressing the advantages and disadvantages of different sampling methods for large natural areas. According to Stohlgren et al. (1995), there are no off-the-shelf sampling designs and techniques for optimizing geographical, ecological and taxonomic completeness in a habitat. An important assumption which one must accept in adopting sampling surveys is that information on occurrence of non-indigenous species, and the associated variables, which have been collected using unbiased survey designs, has potential application in the production of probability maps of species' occurrence in areas which have not been surveyed (Rew et al. 2005; Franklin 1995; Guisan and Zimmerman 2000; Shafii et al. 2003).

The primary objective of weed surveying and mapping is to accurately identify and delineate land with populations of unwanted plants. One of the objectives of the current study is to design and utilize sampling techniques for conducting surveys on weed infestation of highways' right-of-ways in Mn/DOT's District 4, Minnesota.

3.3 Population predictive modeling

Modeling offers an alternative means for predicting weed abundance and distribution over large landscapes. Findings from studies on use of predictive models to assess species occurrence or potential for invasion in landscapes have been reported in various publications. Higgins et al. (1996, 2000) and Collingham et al. (1997) present theoretical weed spread models within a GIS. These models are designed to predict weed population growth and dispersion based on biological attributes and environmental interactions. Habitat suitability models for potential weed existence are difficult within a GIS because one of the most important environmental predictors for invasion is the frequency and extent of disturbance (Hobbs & Huenneke, 1992). Data on frequency and extent of disturbance is not commonly available in geographic data layers.

Ongoing research on development of empirical invasion models that can predict which species are likely to invade certain environments have been reported in various literature (e.g. Richardson et al. 1990; Tucker and Richardson 1995; Rejmanek and Richardson 1996). Findings obtained in various studies support continued research into use of these models. However, little is known about rates and spatial patterns of invasive plant spread (Macdonald, 1993). According to Higgins et al. (1996), the magnitude and nature of the impacts of alien plants on natural systems demand the development of a framework for predicting alien plant spread. Gillham et al. (2004) has reported on models used to predict potential risk for invasion by an individual species in rangelands. The model determines potential for invasion by comparing growth requirements of each weed species with respect to nine site characteristics (distance from water and disturbance sources, elevation, annual precipitation, soil texture and pH, aspect, slope, and land cover) obtained from geographic data layers.

3.4 Current Mn/DOT Sampling Design

The Minnesota Department of Transportation (Mn/DOT) has been conducting surveys and recording data on weed infestation in rights-of-way (ROWs) of roads it manages in District 4. The surveys which were initiated in 2000, have adopted procedures described below. The main objective of the surveys is to gather information on infestation by weed species in the State list of prohibited noxious weeds, which will then be applied in mapping population dynamics and assessing effectiveness of control measures. Answers to the questions on whether the infestations are decreasing, increasing and/or migrating are critical in decisions by managers in Mn/DOT and agencies concerned with weed management. The surveys have been conducted following a survey model, hereon referred to as the Current Mn/DOT Model.

The survey involved use of samples for smaller areas within the District. The sample comprised of seven three mile long segments (Table 3.1), selected following criteria described by the District 4 maintenance unit (Supervisor, personal communication, 2004). One of the aims in adopting the criteria used in this selection was to ensure that the diverse conditions in the District were equitably represented in the final selected sample. The criteria took into account the following road location attributes:
Urban or Rural setting
Direction of road orientation: North-South or East-West
Landuse /land cover - Wooded areas or Non-wooded

The survey data was recorded using Trimble Pro XR® Global Positioning System (GPS) units. Three weed species Canada thistle (Cirsium arvense L. Scop.), Leafy spurge (euphorbia esula L.) and Poison ivy (Toxicodendron radicans), which are problem weeds of the region, have been of special interest in the surveys.

Table 3.1: Survey sample segments selected in District 4 (2000-04 survey model)

Segment ID	Road Name	Mile Marker range	Road Edge Miles*
40	MN59	231-234	6
41	MN75	191-194	6
42	MN55	21-24	6
43	MN235	2-5	6
44	MN29	83-86	6
45	I-94	111-114	9
46	MN27	66-69	6

* Road edge miles here refers to the sum of total miles of the 2 sides and median (where available) of highway rights-of-way

These seven segments reportedly represent approximately one percent (1%) of the total miles of highways ROWs in Mn/DOT's District 4. Questions have been raised by Mn/DOT on whether this sample size and sampling intensity is adequate and statistically valid for applications to estimate weed population and distribution in the entire District 4.

3.5 New Sampling Design

The current project was proposed purposely to attempt to answer the questions on statistical validity of the current Mn/DOT sampling design, subsequently develop a statistically valid survey model. Surveys conducted in the summers of 2004 and 2005 adopted both the current Mn/DOT procedures, and new design(s) developed in this project. Selection of new sampling sites for weed surveys in the FY2004 season involved tabulating mile marker points, at quarter (0.25) mile intervals, for all MNDOT managed road miles in District 4. From this population, a sample of 105 points was obtained through complete random selection. Because of differences in the length of the individual roads traversing the District, the longer roads with a higher number of mile marker points had higher representation, while shorter roads had little or no representation in the obtained sample. Further, the obtained sample sites were found to be poorly distributed over the District, with some large sections of the study area missing sampling sites. This necessitated conducting an additional "biased" selection of points to cover unrepresented areas in the District. This correction, however, failed to address influence of variations in land characteristics over the study area on weed occurrence and distribution. Although this sample had potential for higher accuracy in predicting areas with potential for infestation by target weed species compared to the current Mn/DOT model, it could be further improved upon. Selection of a sample with sites well distributed over the study area (District 4), which has an equitable representation across pertinent land classes, is critical in successfully addressing stated project objectives.

A possible way this survey model could be improved is to adopt a weighted stratified sampling technique, instead of the complete random sampling procedure applied over the entire study area. Stratified sampling is a commonly used probability method that is superior to random sampling because it reduces sampling error. Land ecological classes bear significant influence on occurrence and distribution of certain weed species will be part of the variables to be applied in the stratified sampling design.

To facilitate selection of a well distributed sample representative of the study area, land ecological data was acquired from the Minnesota Department of Natural Resources (DNR) Data Deli (http://maps.dnr.state.mn.us/deli/). The data was imported into ArcMap/ArcView GIS platform, reclassified into the main natural classes, and then clipped to obtain a map for the study area. Using the ArcView/ArcMap Geoprocessing Tools, the classified map layer and mile point layer was subjected to intersection analysis, producing sub-layers for each ecological zone. Road mile marker points falling in a given zone were tabulated. A predetermined sample size was randomly selected based on start points of quarter (¼) mile marker points. By pooling these points from all ecological classes, a final sample was obtained to be used in the survey.

3.6 Modification of Data Dictionary

For improvement on value and adaptability of the data obtained, as well as its applications in modeling, more parameters were included in the GPS data dictionary for the FY2005 surveys.

Interaction among vegetation species across diverse land characteristics is known to influence biodiversity and distribution of plant species. To take into account other land characteristics known to influence vegetation occurrence and distribution, the GPS data dictionary was modified to enable recording of information on the following parameters:
Names (and photographs) of dominant vegetation type(s) within weed patch
Site location (include name of highway and mile marker point)

Further information obtained includes:
Land use/ land cover at location of recorded weed patch (observed and from DNR Data Deli)
Soil type at location of recorded patch (observed and from DNR Data Deli)
Slope/elevation of site with weed infestation (from DEM, DNR Data Deli)

This information will be important during data analysis, and useful when trying to explain some peculiarities in weed distribution.

3.7 Data Collection and Analysis

The two survey procedures described above were applied during field work and data collection in YR2005. Mn/DOT personnel surveyed three-quarters of the quarter-mile segment sites (Table 2.2 and 2.3), as well as all three-mile segments (Table 3.1). Mode of collection involved use of 4-wheel 'ATVs' driven around the perimeter of each weed patch within sampling sites. A weed patch was arbitrarily defined as "contiguous infestation, larger than the 4-wheeler (approximately 5 x 8 feet), with infestation density of ten percent or more".

University of Minnesota staff surveyed the remaining quarter-mile segments. The staff drove to each segment location, and then walked each infestation patch, recording data with GPS units. Recorded attribute data were guided by the GPS dictionary, which is published in the final user's guide.

Total weed infestation (acres) in each sub-region was computed from the obtained data. From the same data and total road miles, mean infestation (acres/mile) was determined per region and for each percent cover category (10-32, 33-65 and 66-100%).

Similarly obtained parameters will also be evaluated from data acquired using the surveying method currently adopted by MN/DOT. Validation of the existing survey method will then be carried out by conducting cross analysis of the obtained, comparable infestation values (totals and mean per road length for each sub-region).

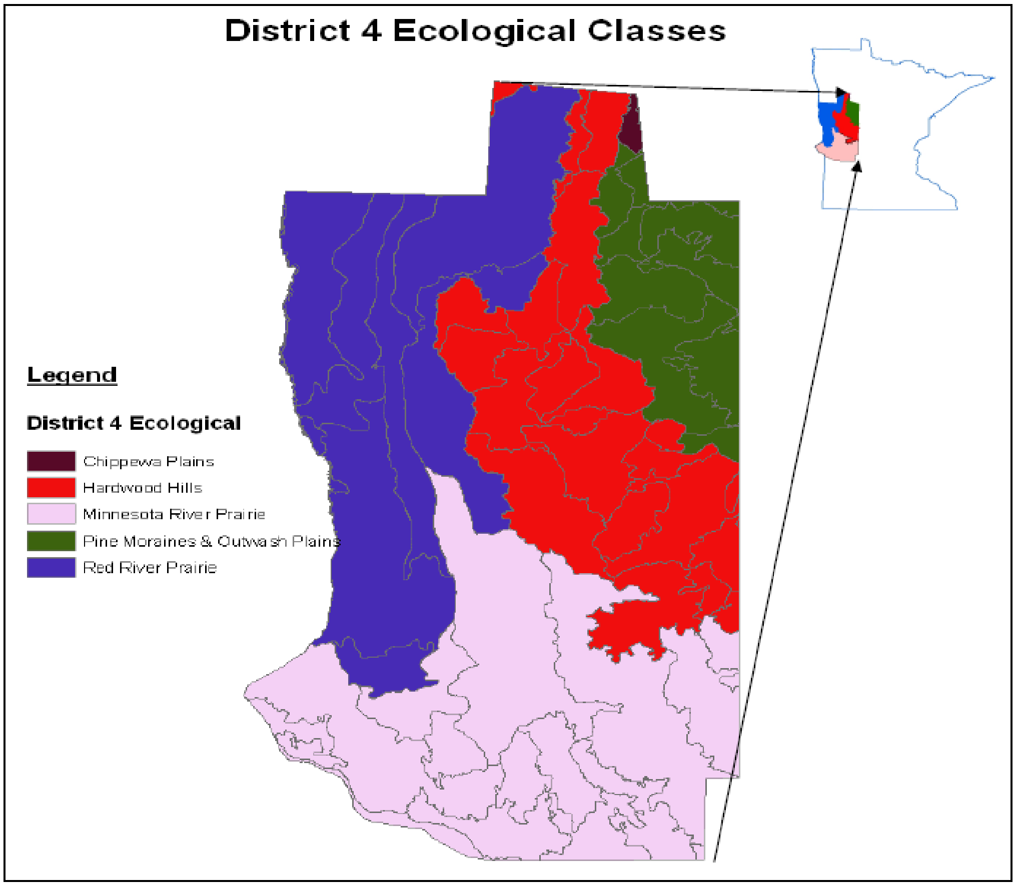


Figure 3.1: Ecological Zones of Mn/DOT District 4, Minnesota

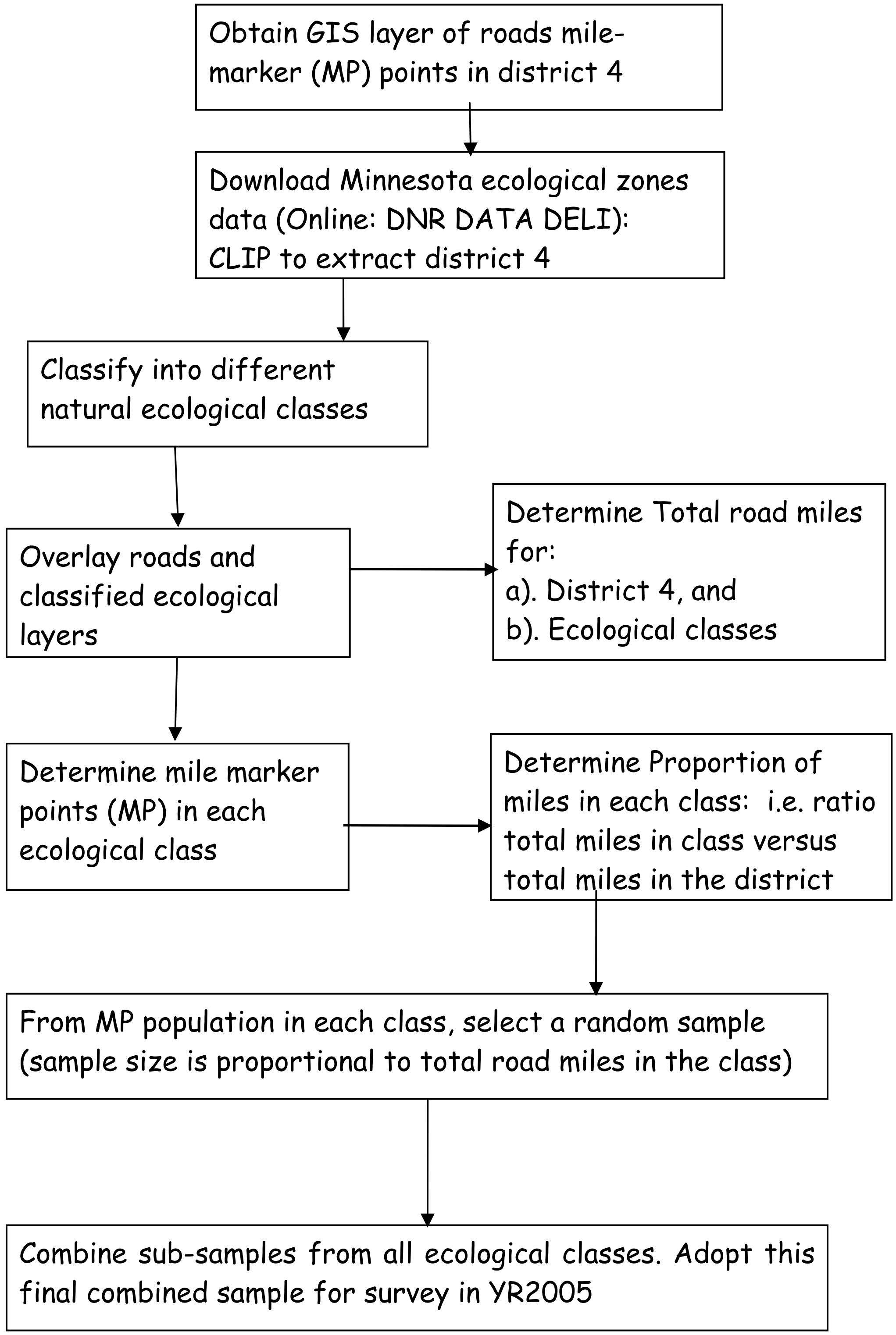


Figure 3.2: Criteria for Selection of Sampling Sites using ArcGIS

Table 3.2: Quarter-mile Survey sample segments selected based on the proposed selection criteria, for surveys conducted in YR2005, District 4, Minnesota

SAMPLE OF QUARTER-MILE SEGMENTS ADOPTED IN FY2005 SURVEYS						
Sites Surveyed by U of M Staff and Students						
	S/No.	GIS_ ROUTE	REF_ POST	Northing	Easting	Ecozone
1	249	MN114	1.50	5055910.69	302690.74	Minnesota River Prairie
2	1	MN200	66.00	5244502.40	306891.99	Chippewa Plains
3	422	MN210	11.25	5131009.53	238362.00	Red River Prairie
4	480	MN210	77.25	5132375.48	337908.50	Hardwood Hills
5	491	MN224	4.00	5219505.84	283792.77	Red River Prairie
6	531	MN27	29.75	5077672.73	236636.45	Red River Prairie
7	520	MN27	88.25	5081990.09	327203.37	Minnesota River Prairie
8	1249	MN55	75.25	5052570.12	319414.41	Minnesota River Prairie
9	1016	MN78	46.50	5159941.49	302698.17	Hardwood Hills
10	1626	MN9	33.25	5022267.48	299959.19	Minnesota River Prairie
11	1582	MN9	46.75	5034213.44	286821.45	Minnesota River Prairie
12	1096	MN9	168.75	5204303.61	233186.93	Red River Prairie
13	1206	US10	19.75	5196961.45	242898.79	Red River Prairie
14	1108	US10	58.25	5173224.57	295615.08	Hardwood Hills
15	1120	US10	61.25	5168964.02	297868.37	Hardwood Hills
16	2131	US59	177.25	5068809.26	275787.96	Minnesota River Prairie
17	1236	US59	256.50	5178275.64	279366.27	Hardwood Hills
18	2306	US75	148.00	5041226.29	231658.41	Minnesota River Prairie
19	2292	US75	151.50	5046009.49	231977.46	Minnesota River Prairie
20	2338	US75	160.75	5060452.48	233004.67	Minnesota River Prairie
21	1544	US75	178.50	5088242.75	229169.65	Red River Prairie
22	1535	US75	180.75	5091489.06	229319.24	Red River Prairie
23	1835	US75	220.75	5150230.39	216018.38	Red River Prairie
24	1695	US75	263.25	5216524.34	213076.02	Red River Prairie
25	Replace ment	MN87	11.50	5180895.47	306738.96	Pine Moraines & Outwash Plains
26	Replace ment	MN28	51.75			Minnesota River Prairie
	Sites Surveyed by Mn/DOT Staff					
1	84	I94	24.75	5173762.49	239856.32	Red River Prairie
2	100	I94	28.75	5168210.68	243087.90	Red River Prairie
3	105	I94	30.00	5165260.61	244379.75	Red River Prairie
4	20	I94	95.75	5086432.58	304144.35	Hardwood Hills
5	106	I94	105.25	5078510.75	317396.61	Minnesota River Prairie
6	107	I94	105.50	5078510.75	317396.61	Minnesota River Prairie
7	128	MN108	31.00	5159496.64	290739.73	Hardwood Hills
8	132	MN108	32.00	5159473.54	292357.75	Hardwood Hills

Table 3.2: (cont….)

SAMPLE OF QUARTER-MILE SEGMENTS ADOPTED IN FY2005 SURVEYS						
Sites Surveyed by U of M Staff and Students						
9	137	MN108	33.25	5159406.06	293976.42	Hardwood Hills
10	291	MN200	58.75	5244792.75	294068.22	Hardwood Hills
11	3	MN200	66.50	5244502.40	306891.99	Chippewa Plains
12	313	MN210	34.25	5129642.54	272925.86	Hardwood Hills
13	150	MN225	1.75	5204534.93	320283.33	Pine Moraines & Outwash Plains
14	539	MN27	34.50	5077437.40	244677.48	Red River Prairie
15	531	MN27	88.00	5081990.09	327203.37	Minnesota River Prairie
16	617	MN28	23.75	5052180.24	232878.76	Minnesota River Prairie
17	677	MN28	42.50	5050890.42	263430.52	Minnesota River Prairie
18	706	MN28	52.00	5054378.30	277374.77	Minnesota River Prairie
19	851	MN29	23.25	5005831.91	296200.88	Minnesota River Prairie
20	874	MN29	29.00	5015252.53	295748.48	Minnesota River Prairie
21	685	MN29	96.00	5106727.83	320393.17	Hardwood Hills
22	739	MN29	110.75	5129082.08	321170.48	Hardwood Hills
23	562	MN32	0.25	5172390.32	252446.66	Red River Prairie
24	677	MN32	34.25	5226357.37	252893.23	Red River Prairie
25	695	MN34	2.25	5172882.92	241563.52	Red River Prairie
26	265	MN34	58.00	5195726.51	316818.48	Pine Moraines & Outwash Plains
27	288	MN34	63.75	5198406.50	324101.39	Pine Moraines & Outwash Plains
28	1248	MN55	75.00	5052570.12	319414.41	Minnesota River Prairie
29	1386	MN7	22.75	5028374.14	228118.37	Minnesota River Prairie
30	1456	MN7	52.25	5005925.46	265685.80	Minnesota River Prairie
31	868	MN78	8.25	5109630.14	287512.54	Hardwood Hills
32	893	MN78	14.50	5116084.28	290907.84	Hardwood Hills
33	1515	MN79	11.25	5097079.38	287038.07	Minnesota River Prairie
34	351	MN87	11.75	5180895.47	306738.96	Pine Moraines & Outwash Plains
35	385	MN87	20.25	5181112.58	320948.28	Pine Moraines & Outwash Plains
36	1650	MN9	52.75	5042553.58	281956.86	Minnesota River Prairie
37	1658	MN9	54.75	5044253.70	279256.98	Minnesota River Prairie
38	977	MN9	137.75	5157812.38	233118.11	Red River Prairie
39	993	MN9	141.75	5164085.56	234602.21	Red River Prairie
40	1078	MN9	164.25	5197850.85	232920.56	Red River Prairie
41	1026	US10	27.50	5196471.27	255778.11	Hardwood Hills
42	1779	US12	8.75	5021346.55	241690.22	Minnesota River Prairie

Table 3.2: (cont….)

SAMPLE OF QUARTER-MILE SEGMENTS ADOPTED IN FY2005 SURVEYS						
Sites Surveyed by U of M Staff and Students						
	S/No.	GIS_ ROUTE	REF_P OST	Northing	Easting	Ecozone
43	1794	US12	12.50	5021096.88	248127.55	Minnesota River Prairie
44	1812	US12	17.00	5020710.45	256175.28	Minnesota River Prairie
45	1849	US12	26.25	5018563.08	269869.75	Minnesota River Prairie
46	1905	US12	40.25	5021044.21	291753.10	Minnesota River Prairie
47	2018	US59	147.75	5022579.80	271779.09	Minnesota River Prairie
48	2038	US59	152.75	5030629.20	272071.82	Minnesota River Prairie
49	1294	US59	228.50	5142916.95	259435.42	Red River Prairie
50	1320	US59	236.25	5154850.08	263011.68	Red River Prairie
51	1170	US59	237.75	5156452.24	263080.42	Hardwood Hills
52	1258	US59	262.00	5186923.85	280448.93	Hardwood Hills
53	1266	US59	265.25	5190985.54	282043.70	Hardwood Hills
54	1283	US59	269.50	5196506.80	279070.03	Hardwood Hills
55	1416	US59	296.75	5239595.24	278130.39	Red River Prairie
56	1442	US59	303.25	5250098.71	275805.06	Red River Prairie
57	1471	US59	311.75	5262963.42	275789.23	Red River Prairie
58	2221	US75	129.00	5018076.52	239873.98	Minnesota River Prairie
59	1516	US75	173.75	5080230.11	228859.41	Red River Prairie
60	1767	US75	240.00	5181804.56	212853.57	Red River Prairie
61	1790	US75	245.75	5189666.53	212489.48	Red River Prairie
62	Replace	mn27	33.75	5077498.62	243063.26	Red River Prairie
63	Replace	MN27	39.75	5077104.69	252720.08	Red River Prairie
64	Replace	MN9	163.00	5196247.08	232864.74	Red River Prairie
65	Replace	US12	16.50	5020790.72	254564.21	Minnesota River Prairie
66	Replace	MN29	28.50	5013647.99	295681.75	Minnesota River Prairie
67	Replace	US12	40.00	5021044.21	291753.10	Minnesota River Prairie
68	Replace	MN78	18.50	5122497.01	291139.76	Hardwood Hills
69	Replace	MN34	63.50	5198406.50	324101.39	Pine Moraines & Outwash Plains
70	Replace	US12	8.00	5021346.55	241690.22	Minnesota River Prairie
71	Replace	MN29	53.25	5051194.46	302531.68	Minnesota River Prairie
72	Replace	I94	105.75	5078510.75	317396.61	Minnesota River Prairie
73	Replace	US59	233.50	5150632.84	261073.89	Red River Prairie
74	Replace	MN9	140.50	5162523.37	234233.37	Red River Prairie
75	Replace	US59	232.00	5149308.03	260177.34	Red River Prairie
76	Replace	MN87	11.50	5180895.47	306738.96	Pine Moraines & Outwash Plains

The above sites were adopted in the YR2005 surveys. Those marked "Replace" were new selections to replace those initially selected but were upon inspection found to have problems. Common problems encountered with some sites included location in areas with road construction, dangerous terrain (un-navigable on foot or ATV), due to heavy rains or high water table, or are within towns where clean mowing was prevalent.

During both the FY2004 and FY2005, all 3-mile long segments previously listed in Table 1 were also surveyed by the Mn/DOT staff.

Chapter 4

Modeling Weed Population Dynamics

4.1 Introduction

This phase of the project is an attempt at simulating infestation of highway rights-of-way by three noxious weed species in the study area (District 4). The species studied were Canada thistle, leafy spurge and poison ivy. The Minnesota department of Transportation is mandated by law to control these species in the rights-of-way of highway under its management. A prerequisite requirement in management of weed populations is availability information on location and character of infestations. This information has traditionally availed by conducting inventories. Modeling has been shown to be a potential source of this information, with lower costs being incurred in the procurement.

A variety of models are available for application in development of weed occurrence maps. The narration in the proceeding sections offer descriptions of some weed models. The objective of this task was to adopt modeling using existing models which can accept the data being recorded in this project to predict infestations and assess effect of applied control measures. Surveys conducted in the course of this project involved recording information describing infestations. This included location, density, position on landscape, among others, of Canada thistle, leafy spurge and poison ivy in the study area. Two survey sampling designs, "Current Mn/DOT Sampling Design" and the "New Sampling Design", have been adopted in selection of survey samples for data collection. The Current Sampling Design, developed by Mn/DOT and adopted beginning 2000, are as described in weed management procedures of Mn/DOT's Alexandria office (Dan Peterson, personal communication), while the "New Design" has been described in the report submitted in fulfillment of deliverable for task 3 of this project.

Data collected following these surveying procedures have various common attributes, including name of species, site characteristics such as topographic position, aspect, and adjacent land use, among others. The New Design was modified to include other attributes, among which are infestation density for each species and name of dominant vegetation within local habitat. Other information including ecological zone, topography, and soil type for the study area has been obtained, and will be used in modeling weed population dynamics.

Model applications planned for in this project are aimed at predicting spatial distribution of subject weed species, and to facilitate evaluation of effect of applied control measures.

4.2 Review of different weed population models:

There has been growing interest in predicting ecological processes. Many ideas have been presented on prediction of population dynamics of biological species. Models, which can be relatively simple or complex, are commonly used to illustrate the interacting elements of a biotic system (Watson, 1985). These include mathematical equations, process based models, and combinations such as GIS technology with either of the preceding models. Superiority of a model would depend mainly on prediction accuracy. Dynamic models of plant growth and competition have to date had little impact on the design of weed management programs mainly because of the intensive studies required for successful parameterization (Park, 2003).

There are a number of factors that influence invasion dynamics, including life history traits of native and exotic species, and physical characteristics of the site such as soil texture and climate (Goslee, 2001). The current level of understanding of the relative importance of these factors on invasion dynamics is limited. A broader understanding of the ecological processes underlying the invasion and spread of weeds can contribute to our understanding of plant ecology, as well as improve our ability to control and eliminate weed infestations (Cousens, 1995); Sheley et al., 1996, 1999). Understanding and predicting the dynamics of weed populations and how they respond to management means that we need to be able to relate changes in population size to a range of demographic variable such as fecundity, germination and mortality ((Freckleton, 1998). The extrinsic factors most responsible for floristic growth and persistence of invasive species are soil, climate, and land use (Radosevich et al, 2003). As reported by Radosevich et al. (2003), many studies have shown that both plant growth and weed invasions occur within certain ranges of soil types (Huenneke et al., 1990), hence one of the criteria that should be used to study or to develop predictive models of invasions is the isolation of soil mapping units that each target species finds suitable (Radosevich et al., 2003). Importance of other environmental properties, such as climate, competitors, …

Following is a review of some of the well known models and equations used in predicting population dynamics of biological organisms.

For simplification and clarity, models have been grouped into general categories or classes.

4.2.1 Mathematical Models

This group comprises models which utilize mathematical equations to calculate population.

<u>Fisher Equation</u>

The fisher equation is a well known population dynamics model first proposed by Fisher (Fisher, 1937) to model the advance of a mutant gene in an infinite one-dimensional habitat. This equation has been adopted in modeling population dynamics of a variety of biological organisms, such as bacteria (Kenkre and Kuperman, 2003), population density of single species (Al-Omari and Gourney, 2002), and in range expansion using microscale data on individual movement for animals (Ammerman and Cavalli-Sforza 1984, Okubo et al. 1989, Andow et al. 1990, all quoted in Holmes et al. 1994). The same equation has been adopted in evaluation of solutions of traveling front (Gourley 2000, Al-Omari and Gourley 2002) as applied in determination species spread in habitats. However, in these applications, there was obvious need to modify the equation for improved accuracy in the simulations.

The Fisher's equation for studying traveling fronts is in the form:

$$\frac{\partial u}{\partial t} = u(1-u) + \frac{\partial^2 u}{\partial x^2}$$

This has been determined to work well when dealing with traveling front in local situations.

Gourley (2000) applied the same equation in the solution of traveling front of the nonlocal equation for a single species. This necessitated modifications to the equation to address nonlocal situations.

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2} + u(x,t)\left(1 - \int_{-\infty}^{\infty} g(x-y)u(y,t)dy\right)$$

The second part in the right side of the equation represents the intra-specific competition for resources, which implies that individuals are competing with both those at their own point in space, and those at other points in the domain.

It has been suggested elsewhere that the Fisher equation need modifications before being used in population dynamics studies. Al-Omari and Gourley (2002) have noted that this model is inappropriate for maturation or developmental delays, calling the usefulness of the equation to question. The same was noted by these authors for the delayed Fisher equation below:

$$\frac{\partial u}{\partial t} = u(x,t)(1 - u(x,t-\tau)) + \frac{\partial^2 u}{\partial x^2}, \tau > 0$$

u(x,t) is the birth rate at position x, and $u(x,t)(1-u(x,t-\tau)$ is the death rate at position x

The authors have also noted that another major problem with adoption of either the Fisher equation or the delayed Fisher equation in population dynamics modeling: that it is very difficult to justify the birth rate, u(t) and death rate u(t)u(t-τ), in the delayed fisher equation, and that models of these kind are inappropriate for maturation or developmental delays (Al-Omari and Gourley, 2002).

The Fisher equation, with modification as given below, was adopted as the basic equation governing the bacterial population u(x,t) at position x and time t, in respect of growth rate parameter (a), competition parameter (b), and diffusion coefficient (D) (Kenkre and Kuperman 2003).

$$\frac{\partial u(x,t)}{\partial t} = D\frac{\partial^2 u(x,t)}{\partial x^2} + au(x,t) - bu^2(x,t)$$

For simplicity, the authors have considered only the one-dimensional situation, which is appropriate to some experiments that have been carried out with moving masks. In one such experiment (A.L. Lin, B. Mann, G. Torres, B. Lincoln, J. Kas, and H.L.
Swinney, unpublished), a mask shades bacteria from harmful ultraviolet light that kills them in regions outside the mask but allows them to grow in regions under the mask.

It was assumed that the growth rate has a positive constant value *a* inside the mask, and a negative value outside the mask. The peak value of the profile, um , will decrease as the mask size is decreased (alternatively as the diffusion coefficient is increased).

The authors offered suggestion that parameters extracted in this manner may be used subsequently for the analysis of moving mask experiments with greater confidence in the reliability of the parameter values.

Partial Differential Equations (Homes et al. 1994)

Partial differential equations (PDE) have been used to model a variety of ecological phenomena. Holmes et al (1994) have stated that while PDEs that are sufficiently realistic to be used in ecological models are usually more difficult to solve than ordinary differential equations (ODE), there are advantages in their use as they allow modelers to incorporate both temporal and spatial processes simultaneously into equations governing population dynamics. In the above cited study, the authors have explored the application of the PDEs to dispersal, ecological invasions, the effect of habitat geometry and size (critical patch size), dispersal-mediated coexistence, and the emergence of diffusion-driven spatial patterning. Organisms are assumed to have Brownian random motion, the rate of which is invariant in time and space. This assumption leads to the diffusion model (Okubo 1980, Edelstein-Keshet 1986, Murray, 1989)

$$\frac{\partial u(x,y,t)}{\partial t} = D\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

where *u(x,y,t)* is the density of organisms at spatial coordinates *x, y* and time *t*, and D is the diffusion coefficient that measures dispersal rate, with units of distance squared per time.

The study concludes that implicit to the formulation of a PDE model is the assumption that the rates of birth, death, and movement can take a continuous range of values in both space and time, failing which, alternative mathematical models are more appropriate. The authors cite an example of situations where organisms reproduce continually and move between discrete patches, recommending that in such a situation may be better modeled by a system of coupled ODEs, citing Levin (1974) and Tilman (1994). They conclude that PDE are useful for examining the interaction between habitat geometry and competitive coexistence.

Although diffusion models have been used successfully to model animal populations with reasonable accuracy, estimates on spread by plant population using reaction diffusion models have largely underestimated the area being invaded, often by orders of magnitude (Radosevich, 2003).

Geometric Mean Population Growth Model (Freckleton and Watkinson, 1998)

To be able to adequately predict weed population dynamics and how they respond to management, it is important to relate changes in population size to a range of demographic variables such as fecundity, germination and mortality. It is essential to describe both the effects of changing mean population parameters on the number of individuals in populations, and how spatial and temporal variations in such parameters may affect population numbers (Gonzalez-Andujar and Perry 1995, Cousens and Mortimer 1995). Freckleton and Watkinson (1998) have argued that population models that are used to predict weed population dynamics typically ignore temporal variability in life-history parameters and control measures, utilizing mean arithmetic population growth rates to predict population abundance. Further, weed populations are subject to intrinsic and extrinsic sources of variability. The intrinsic sources of variability include intraspecific competition and plant-to-plant variability in performance, and the latter being due to competition from crop, variability in weather, control measures, together with a variety of biotic and abiotic agents (Freckleton, 1998).

In the current study, the authors have developed a simple analytical principle assessing how temporal variability may affect weed population persistence and mean abundance. It is their opinion that temporal variability around mean population parameters is likely to decrease population sizes relative to predictions based on arithmetic mean, and that such reductions are potentially large enough, which if ignored will compromise the predictive power of a model. In this developed model, the density of weeds at a time T is related to the initial density at time zero (N_o) through the product of population growth rates from time t = 0 to time t = T-1:

$$N_T = N_o \prod_{t=0}^{T-1} \frac{l_t}{\gamma_t}$$

Where l_t/γ_t is the net population growth rate from time t to time t + 1. l_t is composed of parameters in the life-cycle that when increased tend to increase population growth rate (e.g fecundity, germination, survivorship), while γ_t is composed of parameters in the life-cycle that, when increased, tend to depress population growth rates (e.g. competitive effects, or the effects of control measures).

For the population to persist, the overall geometric (not arithmetic) mean population growth rate must be greater than zero, as presented below:

$$\sum_{t=0}^{T-1} \ln l_t - \sum_{t=0}^{T-1} \ln \gamma_t \geq 0$$

Noteworthy here is that the geometric mean population growth is determined by the product of a series of rates, rather than their sum (Cohen 1996, 1993; Lewontun and Cohen 1969l Tuljapurkar and Orzack 1980).

The authors conclude that predictive models of weed control will over-estimate weed abundance unless they are based on geometric mean population growth rates or include estimates of growth rate variability. It is important that estimation of spatial and temporal variability in weed population growth rates are obtained, or at least an indication given on how inherent variability could affect predictions by models based on arithmetic mean population growth rates.

Matrix models - Population modeling approach for evaluating leafy spurge

Watson (Watson, 1985)) used a transition matrix model to describe the population dynamics of leafy spurge. This approach has been used successfully to develop other weed population models (Cousens 1986, Mortimer 1983, Mortimer et al 1980, Sagar and Mortimer 1976.). An important step in developing transition matrix models is in forming a column vector. In the study on leafy spurge model by Watson (1985) illustrated below, the column vector, N, represents the number of plants in each of the indicated stages of the population:

$$
N = \begin{bmatrix} \text{Number of seeds} \\ \text{Number of basal buds} \\ \text{Number of seedlings} \\ \text{Number of vegetative shoots} \\ \text{Number of flowering shoots} \end{bmatrix}
$$

The values in the column vector changes as population size and structure changes over time.

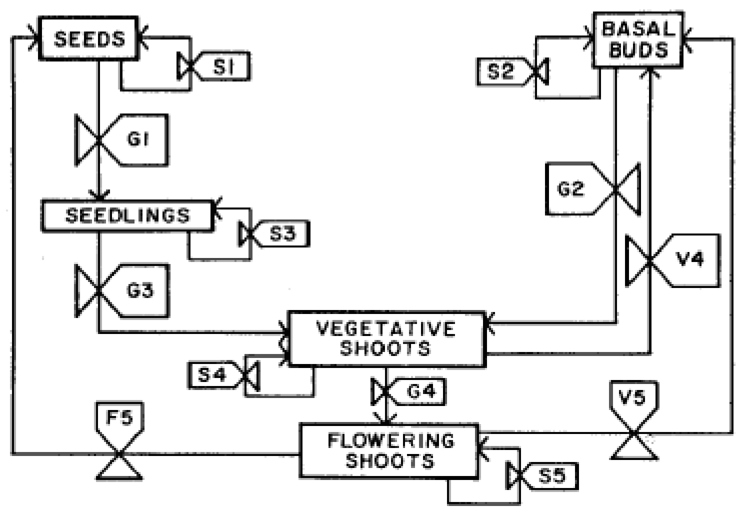


Figure 4.1: Diagrammatic model of a leafy spurge population: the boxes represent stages in the life cycle, arrows indicate processes, and valve symbols represent the rate at which a process occurs over a specific iteration time (Source: Watson, 1985)

The variables of the model transition parameters are:
S1 = proportion of seed that remain viable in the seed bank
S2 = proportion of basal buds that remain viable
S3 = proportion of seedlings that remain seedlings
S4 = proportion of vegetative shoots (non-flowering mature) that remain vegetative
S5 = proportion of flowering shoots that remain flowering
G1 = proportion of seed that germinates to become seedling
G2 = proportion of basal buds that grow to vegetative shoots
F5 = Number of seeds produced per flowering shoot
V4 = number of buds produced per vegetative shoot
V5 = number of buds produced per flowering shoot

The transition matrix summarizes the rates of transition between life history stages for an entire plant population. The transition matrix, M, for the leafy spurge model may be represented as:

$$M = \begin{bmatrix} S1 & 0 & 0 & 0 & F5 \\ 0 & S2 & 0 & V4 & V5 \\ G1 & 0 & S3 & 0 & 0 \\ 0 & G2 & G3 & S4 & 0 \\ 0 & 0 & 0 & G4 & S5 \end{bmatrix}$$

In this transition matrix, the S1 through S5 are the survival rates or the proportion of the individuals that remain in the same stage, F5 represents the production of seeds by flowering shoots, V4 and V5 are the production rates of basal buds on vegetative and flowering shoots, respectively, and G1 through G4 are the rates at which individuals graduate from one stage to another. Zero values mean no transition between stages is possible; for example basal buds do not produce seeds. The columns in the matrix show the fate of individuals which initiate at each of the five life history stages of leafy spurge, while the rows correspond to life history stages that result at a subsequent observation time (t) and show the sources of individuals in the population. The transition matrix and the population column vector are combined through matrix algebra to create an equation describing population changes over time:

$\mathbf{N}(t+1) = \mathbf{MN}(t)$.

This equation indicates that at the next observation time (t+l), the population size and number of individuals in each life history stage [**N**(t+l)] is a result of the transitions (**M**) of individuals contained in life history stages at the current time [**N**(t)]. If the transition rates and population sizes are determined accurately, the procedure should predict the size of future plant population. (Watson, 1985).

4.2.2 Life history models

These types of models utilize physiological and associated data recorded throughout the life history (growth stages) of a plant species.

Spatially-Varying Growth Curve - Modeling weed growth (Banerjee et al. 2005)

Recent advances in Geographical Information Systems (GIS) now allow geocoding of agricultural data enabling sophisticated spatial analysis for understanding spatial patterns. A common problem in use of this technique is capturing spatial variation in *growth patterns* over the entire experimental domain. Statistical modeling in these settings can be challenging because agricultural designs are often *spatially replicated*, with arrays of sub-plots, and agronomists are usually interested in capturing spatial variation at different *resolutions*. In this article the authors have developed a frame- work for modeling spatially-varying growth curves as Gaussian processes that capture spatial associations at single and multiple resolutions.

Non-spatial growth curve models

When spatial variation in the growth patterns is insignificant, simple non-spatial growth curve models may be adequate for data analysis. In the absence of spatial variation, the micro and macro level growth patterns may be indistinguishable; in this scenario subplots are treated as individual locations, observing the respective growth curves. Letting $N = N_s N_r$ to represent the total number of locations, and Y_{it} being the response (weed density in the log scale recorded for location *i* in time *t*), then applicable basic growth curve model is

$$Y_{it} = x_{it}^T \beta + f_i(t) + \epsilon_{it}, i = 1,..., N$$

where x_{it} is a vector of covariates specific to the i^{th} location, $f_i(t)$ is a function capturing the growth through time and ϵ_{it} is measurement error following $N(0, \tau^2)$. Note that we will assume $f_i(t)$ to be linear in *t*, based upon the empirical evidence from the raw data.

This Equation encompasses several non-spatial growth curve models by specifying $f_i(t)$. For example, if no variation in growth patterns is expected between locations, a *uniform* growth curve model, where $f_i(t)$ does not depend upon *i* will suffice. Taking α_0 and α_1 as independent normal coefficients or as correlated with covariance matrix Λ we have the following two models:

Model 1a: $f_i(t) = \alpha_0 + \alpha_1 t; \alpha \sim N(0, Diag(\sigma_0^2, \sigma_2^2))$

Model 1b: $f_i(t) = \alpha_0 + \alpha_1 t; \alpha \sim N(0, \Lambda)$

Single resolution spatial growth curve models

It is reasonable to expect similar growth patterns in locations of close proximity; such locations would share similar topographic and environmental conditions, hence would possess similar baseline growth (intercept) and growth rates (slope). In other words, the growth curves are likely to be *spatially associated* and should be modelled as a function of distance between locations: as this distance increases the association diminishes. There is significant scientific interest in capturing this phenomenon, studied through spatial models.

Spatial models may be classified as single-resolution and multi-resolution. This may be presented in the form:

$N = N_s N_r$

where N is the total number of locations considered for modelling and $Y_t(s)$ is the weed density in subplot *s* at time *t*. . Also, $x_t(s)$ is the associated vector of covariates, and we now write the model as

$$Y_t(s) = x_t(s)^T \beta + f(s,t) + \epsilon_t(s),$$

where $f(s,t) = \alpha_0(s) + \alpha_1(s)t$ and $\epsilon_t(s)$ are i.i.d. $N(0,\tau^2)$

Competition and Biodiversity (Tilman 1994; Alvarez-Buylla and Slatkin 1994, Goldwasser et al. 1994)

Living organisms interact at varying levels with others within the habitat as well as with others outside the habitat. This is known to influence success of any individual species in colonizing the habitat. The dynamics and diversity of a community depend not only on neighborhood interactions, but on the dispersal of organisms among neighborhood (Horn and MacArthur 1972, Rabinowitz and Rapp 1981, and others). Theory predicts that the best competitor for a single limiting resource should displace all other species from a habitat, independent of their initial densities (Tilman, 1994).

However, there have been theoretical demonstrations that habitat subdivision can allow two species, a fugitive and a superior competitor, to stably coexist as metapopulations (Skellam 1951, Levins and Culver 1971 and others). Levins (1969) proposed a simple, general model for the dynamics of site occupancy (Tilman 1994) in such as system:

$$\frac{dp}{dt} = cp(1-p) - mp$$

where c is the colonization rate and *m* is the mortality (local extinction) rate.

Individuals of a single species often cannot occupy all sites in a habitat. In this situation, an inferior competitor may experience stable coexistence by invading the open portions in the habitat. When such competing species co-occur and interact in a site, it is assumed that the superior competitor (species 1) will always displace the inferior (species 2) one, and that the inferior competitor can neither invade into nor displace the superior competitor (Tilman 1994). This leads to two equations:

$$\frac{dp_1}{dt} = c_1 p_1 (1 - p_1) - m_1 p_1$$

$$\frac{dp_2}{dt} = c_2 p_2 (1 - p_1 - p_2) - m_2 p_2 - c_1 p_1 p_2$$

The superior competitor has the same equation (first equation) as would a species living by itself, and thus is totally unaffected by the inferior competitor. The inferior competitor, species 2, can colonize only sites in which it and species 1 are absent ($1-p_1-p_2$). Species 1 can invade into and displace species 2 (the term $-c_1p_1p_2$ in second equation). Localities would differ in species composition as a result of local biotic displacement, local mortality and colonization.

In a situation where there is multispecies competition, the second equation can take the form below, which is the dynamics on the ith species. There are *n* such equations for *n* species. The dynamics of each species depend on colonization (the first term), on mortality ($-m_ip_i$), and on competitive displacement (last term), and a species is only affected by those which are superior competitors (Tilman 1994, Tilman 1982). Application of the model would require species to be arranged in a simple competitive hierarchy, from the lowest to the highest.

$$\frac{dp_i}{dt} = c_i p_i \left(1 - \sum_{j=1}^{i} p_j\right) - m_i p_i - \left(\sum_{j=1}^{i-1} c_j p_j p_i\right)$$

Using the equation below, it is possible to sequentially calculate, starting with the best competitor, the colonization rate required for each of *n* species to attain its equilibrial abundance, which is locally stable.

$$c_n = \frac{\sum_{i=1}^{n-1} (\hat{p}_i m_i) + \left(1 - \sum_{i=1}^{n-1} \hat{p}_i\right) m_n}{\left(1 - \sum_{i=1}^{n-1} \hat{p}_i\right)\left(1 - \sum_{i=1}^{n} \hat{p}_i\right)}$$

4.2.3 Environmental Data Based Simulation Models

Silvertown and Lovett-Doust (1993)

Plants introduced in a new area do not always succeed to colonize the new location unless disturbances occur to remove environmental barriers in the new region, allowing successful migration of the alien plants (Crawley 1987; Sauer 1988). Many invading species fail after introduction into a new environment (Williamson 1996). Finding out the possible reasons for failures and successes of plant species to survive and increase in range is important for development of techniques to prevent or control introductions and spread (Radosevich et al. 2003). Invasion by any species can be considered successful only if the initial plant population reproduces and increase sufficiently to become self-perpetuating. Cousens and Mortimer (1995) described the radial expansion of such self-perpetuating patches as a front advancing on all sides, with the rate of proportional increase conforming to the equation:

$$\left(\frac{dA}{dt}\right)\Big/_{A} = 2\pi r^2 t \qquad [1]$$

when A equals the area occupied, r is the radius of the population, and t is the time in years or generations. In this model, patches are assumed to grow by half the distance of the previous generation (Cousens and Mortimer, 1995). The model further assumes that successful recruitment continues within the founding population and that the rate of expansion is constant (Radosevich et al., 2003). This model has received limited examination in field studies (Auld 1980; Moody 1988)

Silvertown and Lovett-Doust (1993) provide an equation describing the dynamics of a metapopulation in which a plant species requires a particular type of site for establishment, and such sites are scattered:

$$P_{t+1} = P_t + cP_tV_t - xP_t \qquad [2]$$

where t is time, P is the number of populated sites, and V is the number of vacant sites, x is the rate of extinction of populated sites per population per time interval, whereas the vacant sites are colonized at a rate of c per population per time interval (Radosevich et al., 2003); therefore, xPt and cPt are, respectively, the number of new sites colonized, and number of sites where existing populations become extinct.

WeedTurf Model

A study was conducted to investigate germination characteristics of four annual grass weeds under different soil temperatures and water stresses to calculate base temperatures and base water potentials (Masin et al., 2005). These parameters were used to develop a mathematical model (WeedTurf) describing seedling mergence process by considering the interaction of soil water potential and soil temperature (hydrothermal time). The result of obtained from application of the model in predicting emergence of the four weeds were mixed. Acceptable levels of accuracy were realized for two species; while in the other two results were of very poor accuracy.

The model WeedTurf was developed based on the concepts (Forcella, 1998) of the model WeedCast (Archer et al. 2001) which predict the rate of weed emergence in arable soil. The basic concept of WeedCast model is that seeds of all species accumulate hydrothermal time according to the soil temperature only when the soil water potential is above a base value (Masin et al., 2005). Soil Growing Degree Days (SGDDi) are a combination of soil temperature and soil water potential and are calculated as:

$$SGDD_i = nx\max(T_{si} - T_b, 0) + SGDD_{i-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [1]$$

where $n = 0$ when $\Psi_{si} \leq \Psi_b$, $n = 1$ when $\Psi_{si} > \Psi_b$, T_{si} is the average daily soil temperature at 2.5 cm depth, Tb and Ψ_b are the base temperature and water potential thresholds for each weed species, and Ψ_{si} is the average daily soil water potential at 5 cm depth. For prediction of weed germination of turf (with no sowing date), start of accumulation of SGDD is the first day of the year.

Simulated Population of A. nilotica – SPAnDX (Kriticos, 2003)

SPAnDX is a process-based metapopulation dynamics and phenology model of prickly acacia, *Acacia nilotica*, an invasive alien species in Australia. The model describes the interactions between riparian and upland sub-populations of *A. nilotica* within livestock paddocks, including the effects of extrinsic factors such as temperature, soil moisture availability and atmospheric concentrations of carbon dioxide. The model includes the effects of management events such as changing the livestock species or stocking rate, applying fire, and herbicide application. The predicted population behaviour of *A. nilotica* was sensitive to climate. A climatic analysis using CLIMEX (Sutherst et al., 1999; Kriticos, 2001; Kriticos et al., in press) indicated that *A. nilotica* was occupying only a small portion of its potential range in Australia under current climatic conditions, and that changes in climate variables within the range expected to arise from the enhanced greenhouse effect would increase the potential distribution markedly. The CLIMEX analysis provides a relative indication of the climatic suitability of each location for the plant population under each climate scenario.

Using 35 years daily weather datasets for five representative sites spanning the range of conditions that *A. nilotica* is found in Australia, the model predicted biomass levels that closely accord with expected values at each site. SPAnDXcan be used as a decision-support tool in integrated weed management, and to explore the sensitivity of cultural management practices to climate change throughout the range of *A. nilotica*. The cohort-based DYMEX modeling package used to build and run SPAnDX provided several advantages over more traditional population modeling approaches (e.g. an appropriate specific formalism (discrete time, cohort-based, process-oriented), user-friendly graphical environment, extensible library of reusable components, and useful and flexible input/output support framework).

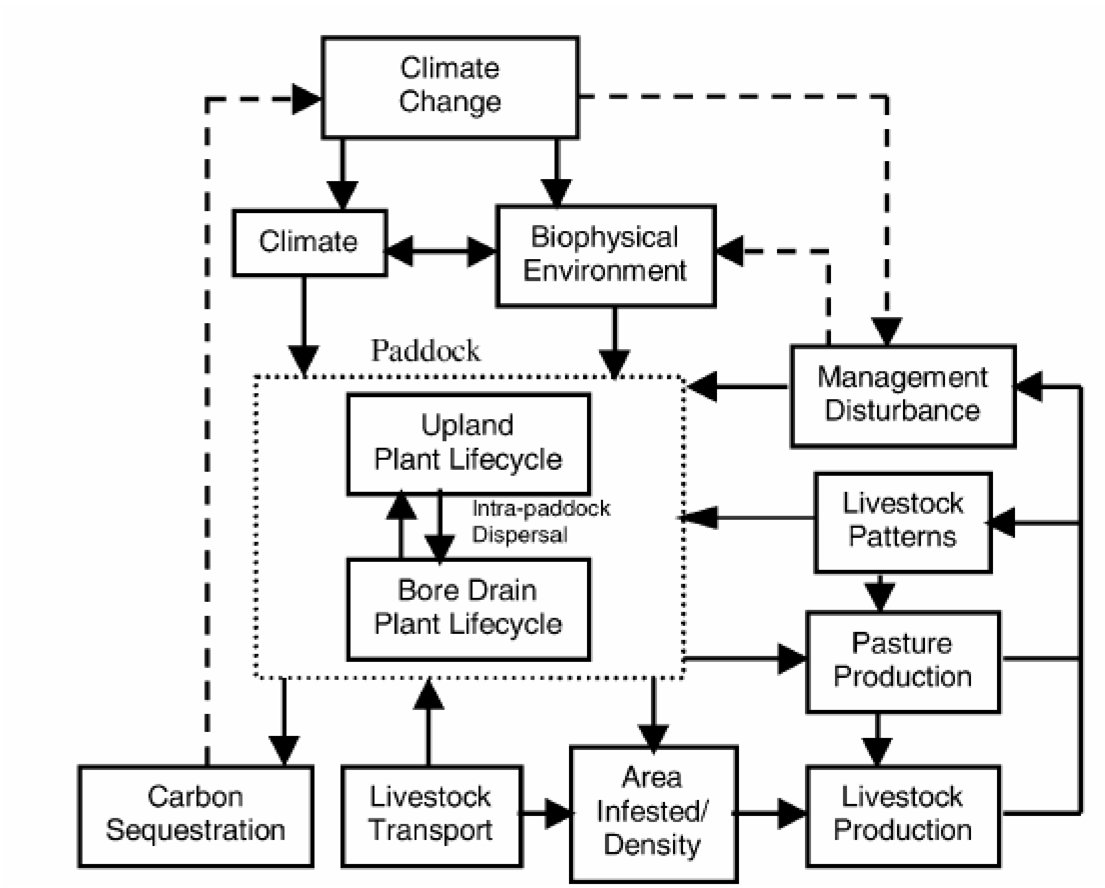


Figure 4.2: Schematic diagram of SPAnDX: Solid lines represent the direct connection while dashed lines represent implicit connections (Source: Kriticso, 2003)

<u>The Weed Invasion Susceptibility Prediction Modeler, WISP (GILLHAM, 2004)</u>

The Model Weed Invasion Susceptibility Prediction Modeler (WISP) was initially developed to assist the USDI Bureau of Land Management (BLM) in managing weed infestations in the Jack Morrow Hills Wilderness study area near Rock Springs, Wyoming. The primary result was an ArcView application for adoption in predicting occurrence and spread of five weed species within semiarid rangelands, namely: black henbane (*Hyoscyamus niger*), hoary cress (*Cardaria draba*), **<u>leafy spurge</u>** (*Euphorbia esula*), perennial pepperweed (*Lepidium latifolium*), and spotted knapweed (*Centaurea maculosa*). WISP Modeler was designed to use nine environmental factors to determine the potential for a weed to exist in a given area. The model consists of two main modules: the Susceptibility Prediction Model and the Spread Model.

The nine factors incorporated in the modeler are:
1. Elevation -- certain weed species can grow at various elevations, but often not higher than a certain value. This factor limits the potential for a weed to exist in elevation ranges that it is not typically found.
2. Slope -- weeds, as with most plants, are limited by the slope angle on which they can establish and flourish. This factor limits the potential for a weed to exist in high slope areas.

3. Aspect -- weeds are more likely to establish on ground facing in certain directions. Most weeds seem to flourish on more south-facing slopes. This, of course, depends on the species.
4. Land Cover -- the type of vegetation predominately occupying an area can determine the ability for a weed species to establish. Some land cover types are more susceptible to weed infestations.
5. Soil pH -- each weed species can grow in soils with a certain pH range. Any soils with a pH outside that range will often limit the growth of that species.
6. Soil Texture -- as with pH, certain species can grow in different soil types. This factor limits the potential for a weed to grow in certain soil types.
7. Precipitation -- if a weed needs a lot of moisture to survive, there needs to be an adequate amount of annual precipitation in an area for that weed. This factor determines where a weed can grow based on the precipitation regime. Some species favor arid climates, whereas other species need more moisture.
8. Distance from Water Sources -- similar to precipitation, this factor limits the places some species can flourish based on the availability of water. A more water-dependent species may need to be located closer to a constant water source in order to survive and invade an area.
9. Distance from Disturbances -- weed species often spread as a result of disturbance in the area, such as pipeline construction or oil and gas development. In fact, some species will spread only because of disturbance in the area.

Database entries were determined from available literature (Lacey et al., 1995; Leitch et al., 1994; Mitich 1992; Sheley et al., 1998; Whitson et al., 1996), reasonable values from expert opinion, and field observations. When a species is not strongly related by distance to either water or disturbance, the parameters for distances to these features were set to an arbitrarily high value. The parameters may be updated by the model user.

Predicting the occurrence of non-indigenous species using environmental and remotely sensed data (Rew, 2005)

This study evaluated use of environmental and remotely sensed (LANDSAT Enhanced Thematic Mapper 1) data, separately and combined, for developing probability maps of three target NIS occurrence. Canada thistle, dalmation toadflax, and timothy were chosen for this study because of their different dispersal mechanisms and frequencies, 5, 3, and 23%, respectively, in the surveyed area. Data were analyzed using generalized linear regression with logit link, and the best models were selected using Akaike's Information Criterion. Probability of occurrence maps were generated for each target species, and the accuracies of the predictions were assessed with validation data excluded from the model fitting.

A stratified sampling approach was used to collect field data. Transects were stratified on rights-of-way (ROW), which include roads and trails in this instance. Field sampling was performed from early June to late August in 2001 to 2003. During the 3 yr, a total of 305 transects were completed. All transects were 10 m wide (most of which were 2,000 m in length, although some were shorter if the terrain proved impassable). The total area surveyed was 53 ha, representing 0.035% of the study area.

Environmental and remote sensing data were used as independent variables. To generate predictive NIS maps of the entire area of interest, we need to have variable information of the entire area. Therefore, we used the environmental data from digital elevation maps (10-m resolution) and remote sensing data (30-m resolution). The environmental data including aspect, elevation, slope, and solar insolation were calculated from 10-m resolution digital elevation map; distance from roads and trails were calculated from data layers within the GIS database. Solar insolation was calculated for the summer months using only Swift's method (Swift 1976). LANDSAT ETM1 remote sensing data, acquired July 13, 1999, were included as individual spectral bands and as an unsupervised classification layer.

The unsupervised classification layer was generated using ISOCLUSTER in ERDAS Imagine,4 and 128 classes were identified. These classes were used by Legleiter et al. (2003) to develop a land-cover map of the Yellowstone watershed with accuracies of between 63 and 100% for individual land cover classes. The 128 individual ISOCLUSTER classes were used in this analysis. The 30-m resolution Bands 1 to 5 and 7 of the LANDSAT ETM1 data were pan-sharpened to 15-m resolution with the panchromatic data from LANDSAT ETM1 Band 8 and re-sampled to 10-m resolution using nearest neighbor re-sampling so that the resolution of the LANDSAT ETM1 data matched the resolution of the digital elevation model available for the study area. All these data layers were queried at 10-m intervals

4.3 Model Development

To make informed decisions on management of noxious weeds, availability to managers, of specific pertinent information on the nature of invasions is critical. This includes total area infested, infestations density, location and total miles of spread of each noxious species. Modeling offers a viable alternative source of required infestation data, normally obtained through inventories.

Modeling efforts conducted in this project employed sample means to to predict total infestation over large areas. Data obtained from surveys conducted in years 2004 and 2005 at randomly selected sampling sites along roadside rights-of-way were used in evaluation of mean acres per mile infested with Canada thistle, leafy spurge or poison ivy. The values were computed for data obtained in each ecological zone and management sub-districts in the study area (District 4).

4.4 Evaluation of means

Mean area infested was evaluated as a ratio of total acres of roadside rights-of-way infested by a given weed species to the total linear miles surveyed in the roadway. (A linear mile refers to the total road miles obtained traveling in one direction of the highway). Mean area infested provides a good indication of the nature of roadside infestations, useful to those interested in analyzing the extent of infestations, such as ecologists. However, managers of highways rights-of-way are typically more interested in controlling infestations. Therefore, information on location, physiological development stage and infestation density of the noxious species would be of critical importance in weed management.

Summaries of mean per-mile infested by Canada thistle, leafy spurge and poison ivy are presented in Tables 4.1 to 4.4, and figures 4.1 and 4.2 below. Comparison of grand means (for entire study area) obtained from the two sampling designs showed mixed results in the two years data, with 2005 data showing no significant differences (table 4.2). However, similar comparisons at ecological zones level, revealed significant differences (tables 4.3 and 4.4).

Table 4.1: Mean acres-per-mile of District 4 rights-of-way infested by Canada thistle, leafy spurge and poison ivy as evaluated from 3-mile and ¼-mile surveys (2004 surveys)

Species	¼-mile (acre/L.mile)	3-mile (acre/L.mile)	N (¼-mile)	N (3-Mile)	¼-mile Confidence Interval	3-mile Confidence Interval
Canada thistle	2.079a ++	1.057b	99	6	0.507	0.758
Leafy spurge	0.005a	0.046b	99	6	0.006	0.063
Poison ivy	0.039a	0.118a	99	6	0.048	0.231

++ Values with the same symbol within a **row** are **not significantly** different (α = 0.05)

Table 4.2: Mean acres-per-mile of District 4 rights-of-way infested by Canada thistle, leafy spurge and poison ivy as evaluated from 3-mile and ¼-mile surveys (2005 surveys)

Species	¼-mile (acre/L.mile)	3-mile (acre/L.mile)	N (¼-mile)	N (3-Mile)	¼-mile Confidence Interval	3-mile Confidence Interval
Canada thistle	2.839a ++	2.437a	100	6	0.640	11.84
Leafy spurge	0.009a	0.004a	100	6	0.011	0.018
Poison ivy	0.163a	0.114a	100	6	0.143	0.674

++ Values with the same symbol within a **row** are **not significantly** different (α = 0.05)

Table 4.3: Mean acres-per-mile of roadway rights-of-way in District 4 Ecological Zones infested by Canada thistle, leafy spurge and poison ivy as evaluated from 3-mile and ¼-mile surveys (2004 surveys)

Species	Ecological Zone	QTR-mile (acre/L.mile)	3-mile** (acre/L.mile)	qtr-mile Confidence Interval (qtr-mile survey)	N
Canada thistle	D4	2.079c++	1.057	0.506	100
	Hardwood Hills	1.419b	1.057	1.242	15
	MN River Prairie	2.297c	1.057	0.813	34
	Pine Moraines	0.270a	1.057	0.271	12
	Red River	2.621d	1.057	0.980	34
Leafy spurge	D4	0.005	0.046	0.006	100
	Hardwood Hills	0.000	0.046	0.000	15
	MN River Prairie	0.010	0.046	0.015	34
	Pine Moraines	0.000	0.046	0.000	12
	Red River	0.003	0.046	0.006	34
Poison ivy	D4	0.039b	0.118	0.048	100
	Hardwood Hills	0.137c	0.118	0.287	15
	MN River Prairie	0.009a	0.118	0.019	34
	Pine Moraines	0.082b	0.118	0.168	12
	Red River	0.000	0.118	0.000	34

++ Values within a **Column** for each species with the same symbol are **not** significantly different ($\alpha = 0.05$)
** 3-mile means refer to grand mean values for the entire study area (District 4)

Table 4.4: Mean acres-per-mile of roadway rights-of-way in District 4 Ecological Zones infested by Canada thistle, leafy spurge and poison ivy as evaluated from 3-mile and ¼-mile surveys (2005 surveys)

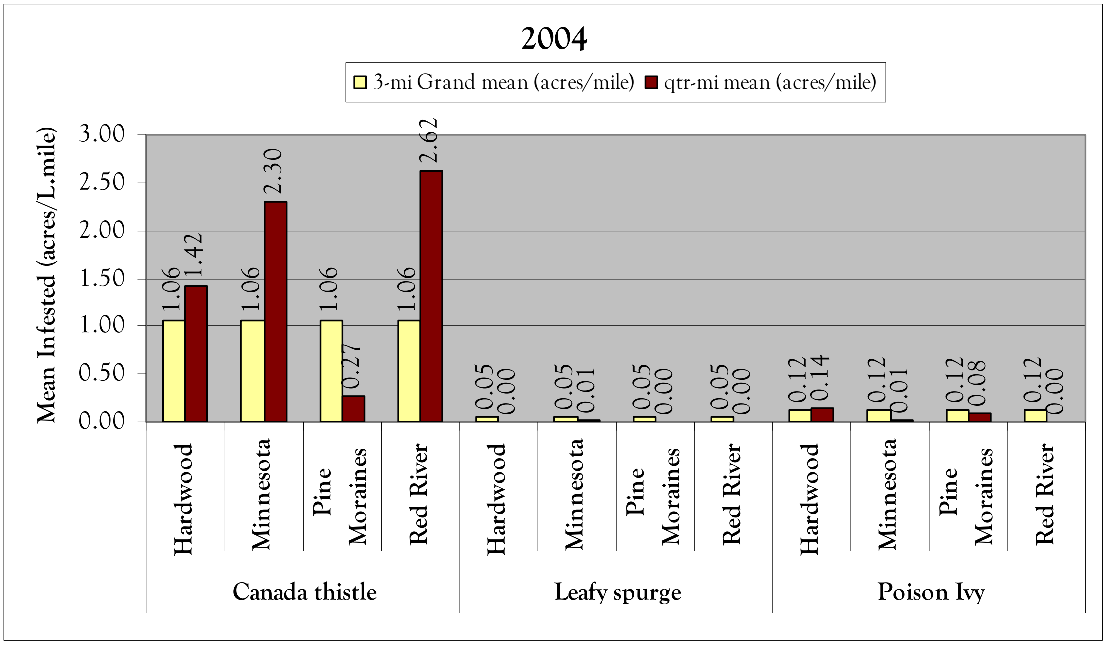
Species	Ecological Zone	qtr-mile (acre/L.mile)	3-Mile Infested (Acres/L.mile)	qtr-mile Confidence Interval (qtr-mile survey)	N
Canada thistle	Overall D4	2.8539b++	2.437	0.640	101
	Pine Moraines	0.307a	2.437	0.287	6
	Minnesota Prairie	2.610b	2.437	0.744	41
	Hardwood Hills	3.079b	2.437	1.751	22
	Red River	3.592c	2.437	1.364	32
Leafy Spurge	Overall D4	0.009b	0.004	0.011	101
	Pine Moraines	0.000a	0.004	0.000	6
	Red River	0.002b	0.004	0.003	41
	Minnesota Prairie	0.006b	0.004	0.005	22
	Hardwood Hills	0.027c	0.004	0.052	32
Poison Ivy	Overall D4	0.163b	0.114	0.143	101
	Red River	0.019a	0.114	0.039	6
	Minnesota Prairie	0.031a	0.114	0.040	41
	Hardwood Hills	0.131a	0.114	0.121	22
	Pine Moraines	1.502b	0.114	2.877	32

++ Values within a **Column** for each species with the same symbol are **not** significantly different ($\alpha = 0.05$)
** 3-mile means refer to grand mean values for the entire study area (District 4)

Table 4.5: Estimated mean acres-per-linear mile and variance of Canada thistle, leafy spurge and poison ivy infestations by ¼-mile sampling design for District 4 and constituent ecological zones (2005 surveys)

Species	Ecological Zone	¼-mile (acre/L.mile)	¼-mile Confidence Interval	N
Canada thistle	Overall D4	2.854b +	0.323	101
	Pine Moraines	0.307a	0.287	6
	MN River Prairie	2.610b	0.744	41
	Hardwood Hills	3.079b	1.751	22
	Red River	3.592c	1.364	32
Leafy Spurge	Overall D4	0.009b	0.011	101
	Pine Moraines	0.000a	0.000	6
	MN River Prairie	0.002b	0.003	41
	Hardwood Hills	0.006b	0.005	22
	Red River	0.027c	0.052	32
Poison Ivy	Overall D4	0.163b	0.143	101
	Pine Moraines	0.019a	0.039	6
	MN River Prairie	0.031a	0.040	41
	Hardwood Hills	0.131a	0.121	22
	Red River	1.502b	2.877	32

++ Values with the same symbol within a **Column** for a species are **not** significantly different ($\alpha = 0.05$)



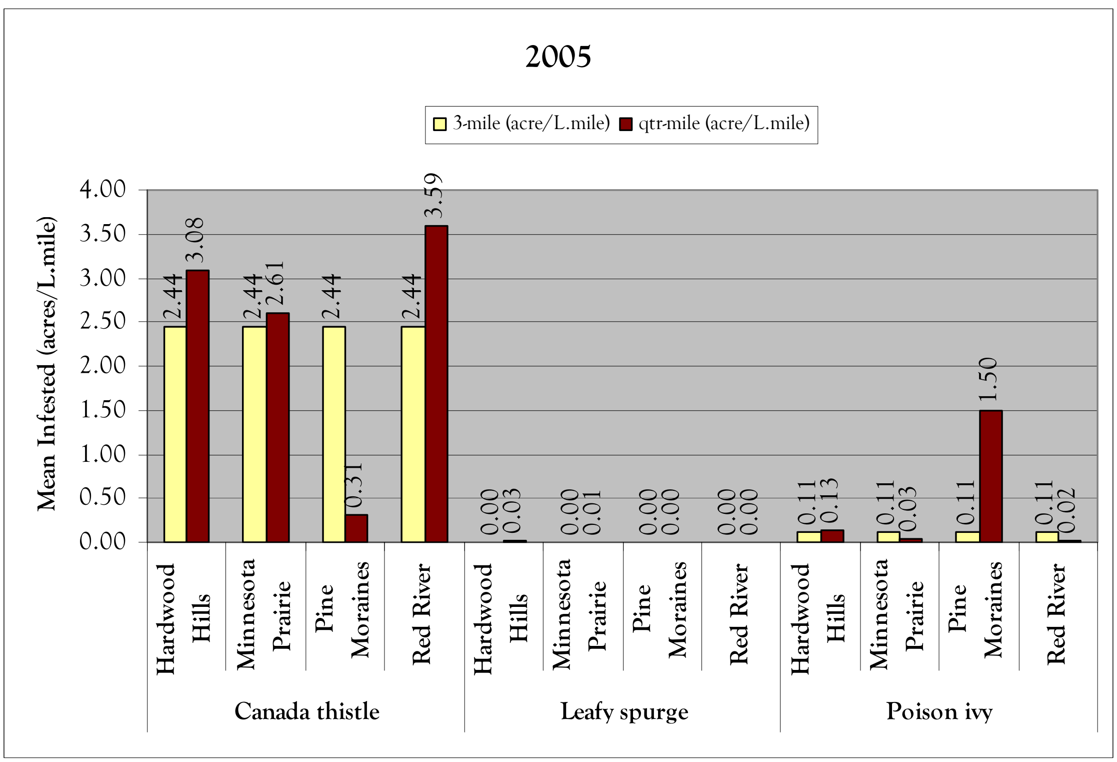


Figure 4.3: Acres-per-mile infested by Canada thistle, leafy spurge, and poison ivy in ecological zones as evaluated from 3-mile & ¼-mile survey means from 2004 and 2005 surveys

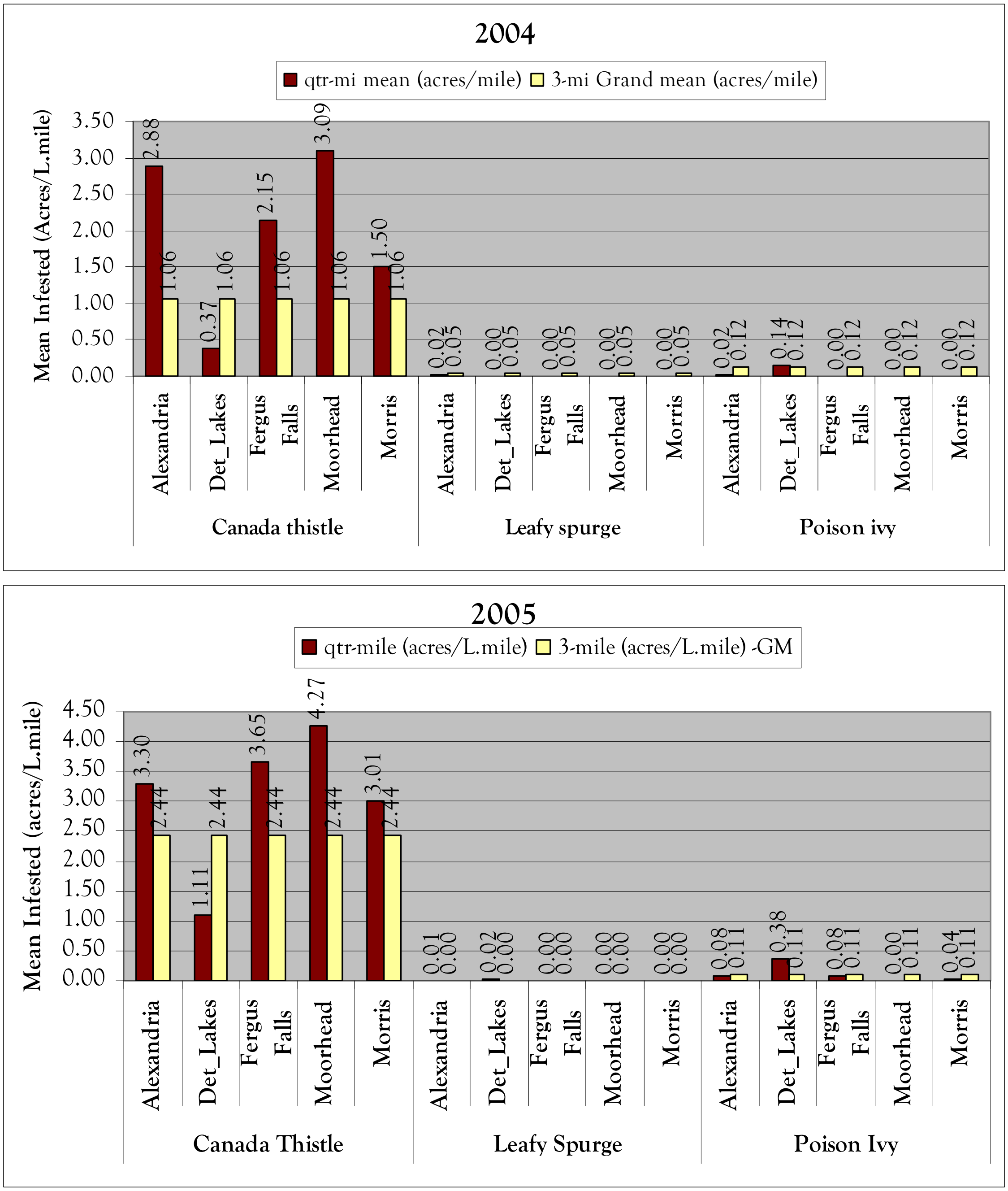


Figure 4.4: Acres-per-mile infested by Canada thistle, leafy spurge, and poison ivy in management sub-districts as evaluated from 3-mile & ¼-mile survey means from 2004 and 2005 surveys

4.5 Total Infested Area

Predictions on total area infested by Canada thistle, leafy spurge and poison ivy were conducted for ecological zones, management sub-districts and for entire the study area (District 4). These determinations were based on data from two sampling designs (3-mile and quarter-mile) adopted in the study for 2004 and 2005. The summary of obtained values is provided in figures 4.3 to 4.5 below. Total infested area for each region (ecological, management sub-district, or District 4) was computed as the product of mean infested and total linear miles of Mn/DOT managed highways in the region. This data offers a broad overview of infestations. However, as previously mentioned, spatial representation is not included.

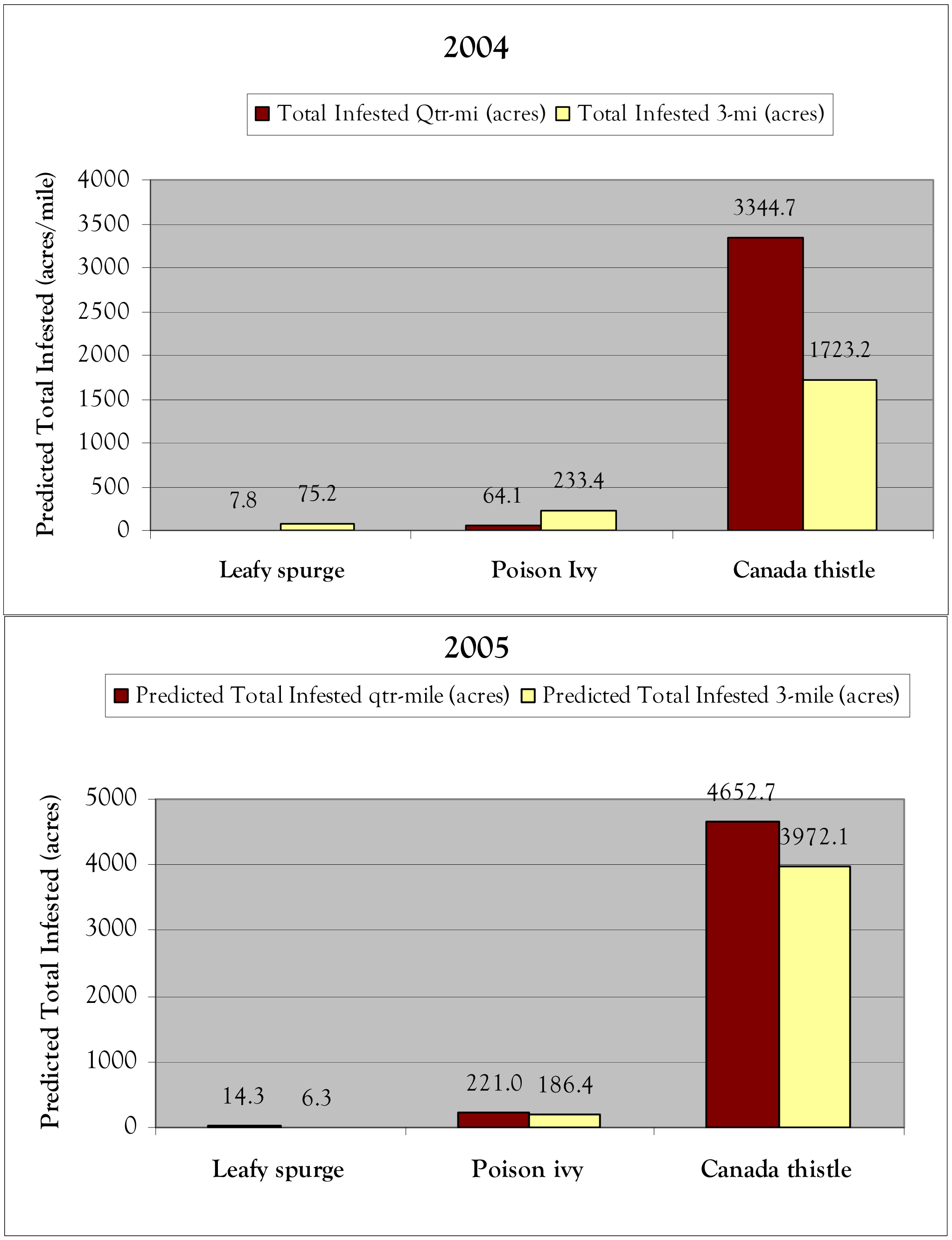


Figure 4.5: Predicted total-acres infested by Canada thistle, leafy spurge, and poison ivy in District 4 based on means from 3-mile & ¼-mile surveys in 2004 and 2005 surveys

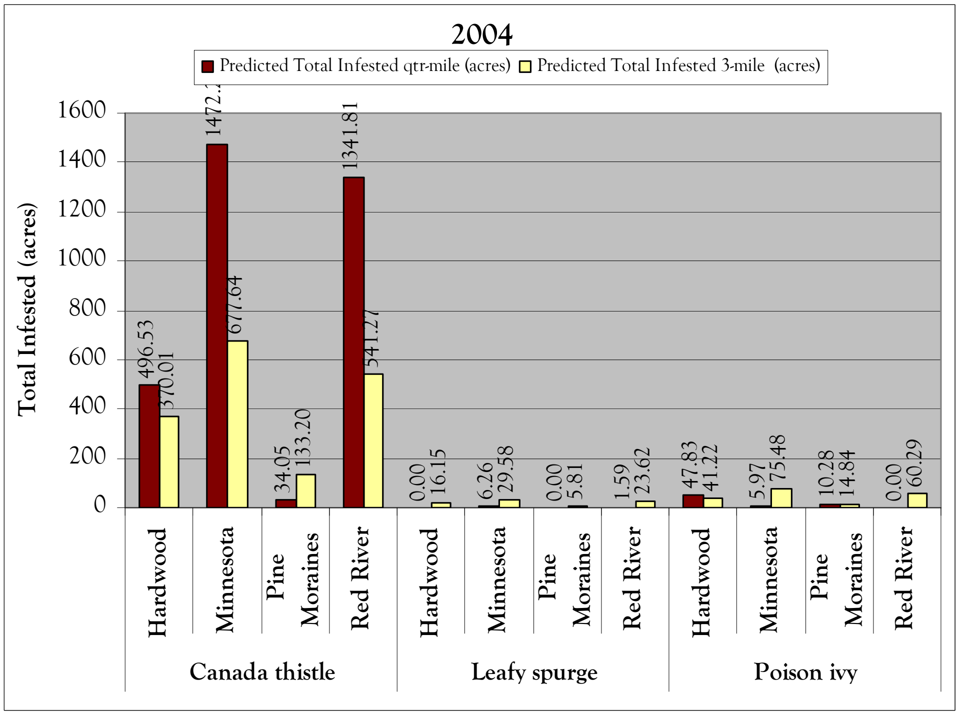


Figure 4.6a: Predicted total-acres infested by Canada thistle in ecological zones as evaluated from 3-mile & ¼-mile survey means in 2004 and 2005 surveys

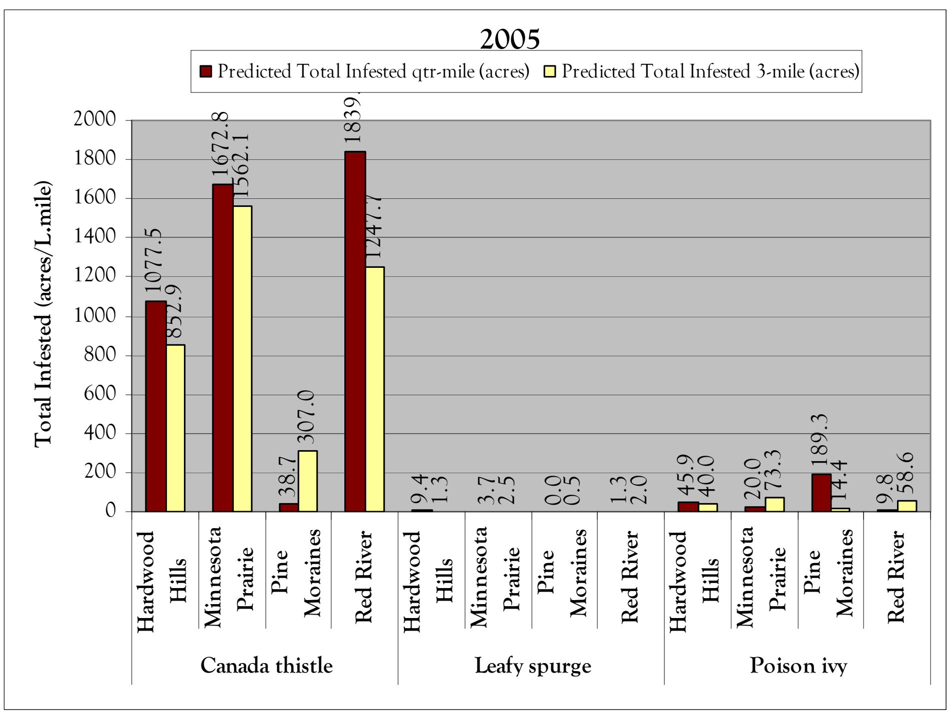


Figure 4.6b: Predicted total-acres infested by Canada thistle, leafy spurge, and poison ivy in ecological zones as evaluated from 3-mile & ¼-mile survey means in 2004 and 2005 surveys

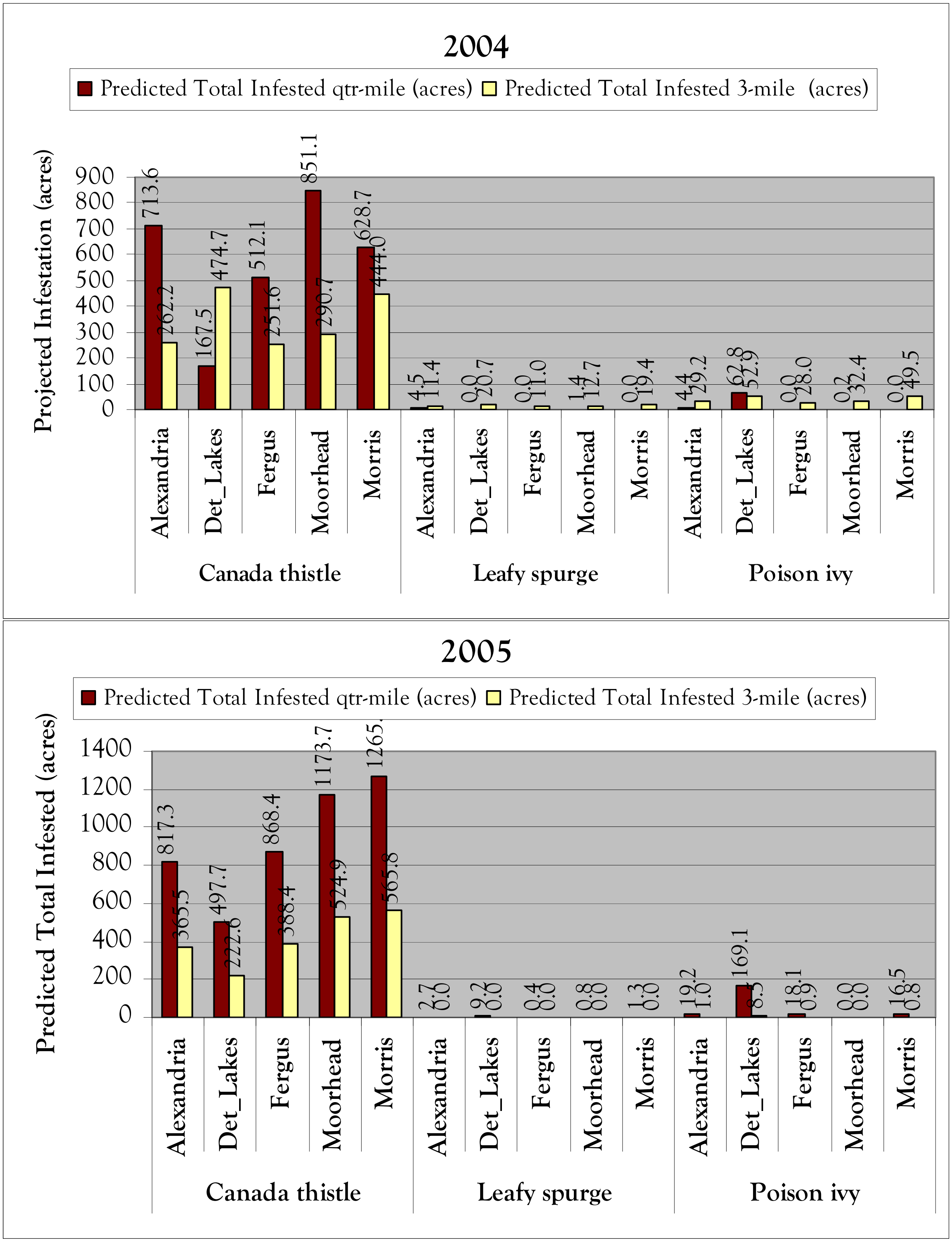


Figure 4.7: Predicted total-acres infested by Canada thistle, leafy spurge, and poison ivy in management sub-districts as evaluated from 3-mile & ¼-mile survey means in 2004 and 2005

4.6 Proportion Infested

The perceived need for information on infestations with a spatial component necessitated evaluation of this parameter, which has potential application in determination of probability of occurrence or absence of species in highways rights-of-way. Proportion infested is the ratio of total number of road edge miles infested by a given species over total miles surveyed (miles infested/miles surveyed). Tho determine total miles infested, we sectioned the highway rights-of-way (ROW) into 20 meter long segments. This was carried out for each of the sides of the highway (right and left sides, and median if highway is divided). Total road edge miles infested by each of the weed species were determined by summing up the 20 m segments in which weeds were found, in all sides (left, right, and median) of the highway.

In this study, data obtained from the sampling surveys was applied in evaluation of road miles infested by each of the noxious species being investigated. An infestation data layer was over-layed (in Arc-GIS 9.0®) with the layer of the 20 m segments generated as described in the foregoing paragraph. This allowed for subdividing infestation patches into 20 m portions, as illustrated in figure 4.8.[A patch section was considered, in preceding analyses, to be 100% infested by a given weed species even when partially covered].

The parameter, proportion mile-per-mile infested, was evaluated by determining both the total road edge miles surveyed in a region and total road edge miles infested by each weed species being surveyed. Road edge miles infested were determined by summing the 20m segments containing infestations over the surveyed highway miles. This value was converted to miles by multiplying it by 20 meters, then dividing by 1,600 meters in a mile. Infested road edge miles were determined for each sampled segment, ecological zone, management sub-district, and entire District 4. The total road edge miles in one quarter mile segment on non-divided highway is half (0.5) miles (or 0.75 for divided highway). Proportion infested (miles-per-mile) was determined by computing the ratio of total road edge miles infested to the total road edge miles surveyed. Obtained values for ecological zones, management sub-districts and entire District 4 are presented in figures 4.9 to 4.11 below. Figure 4.12 shows predicted total miles infested by each species in the study area.

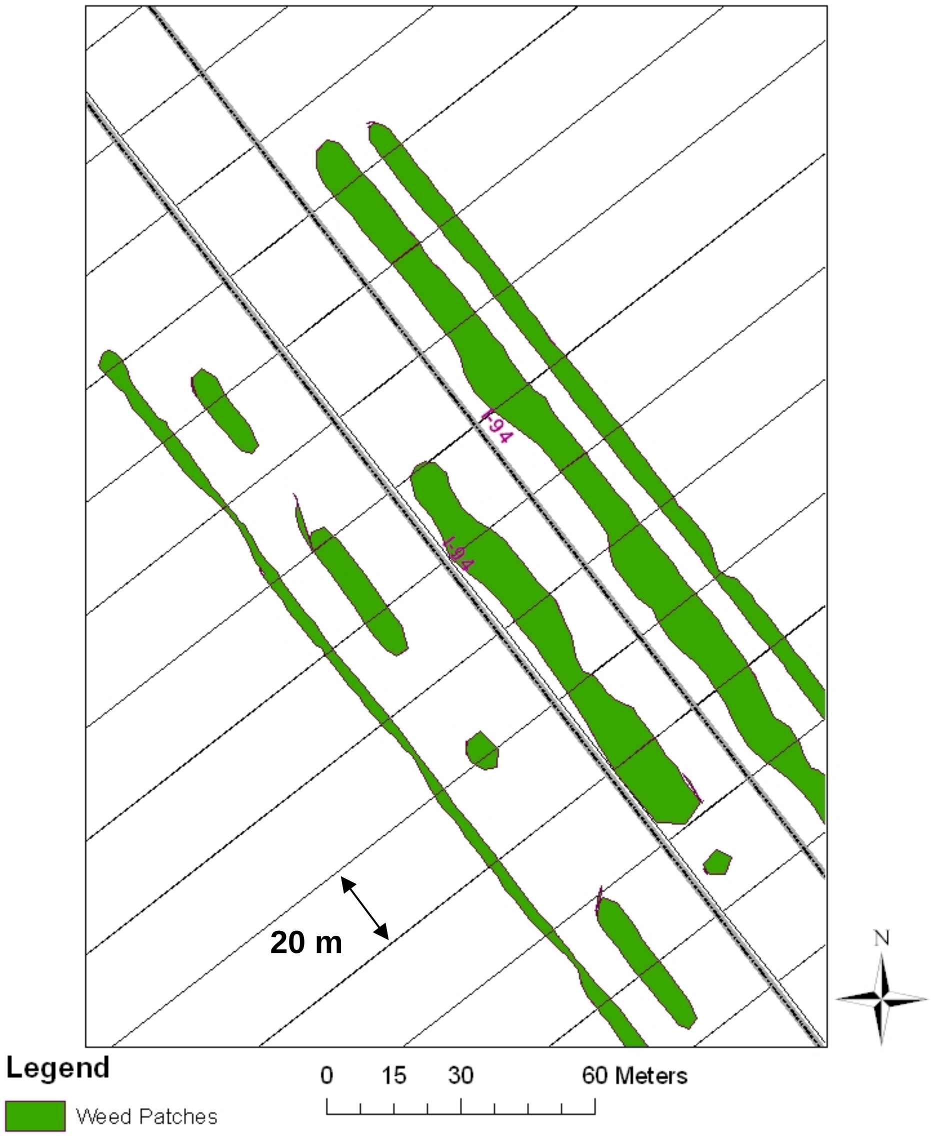


Figure 4.8a: Illustration of sectioning of roadway right-of-way and weed patches into 20 m segment units

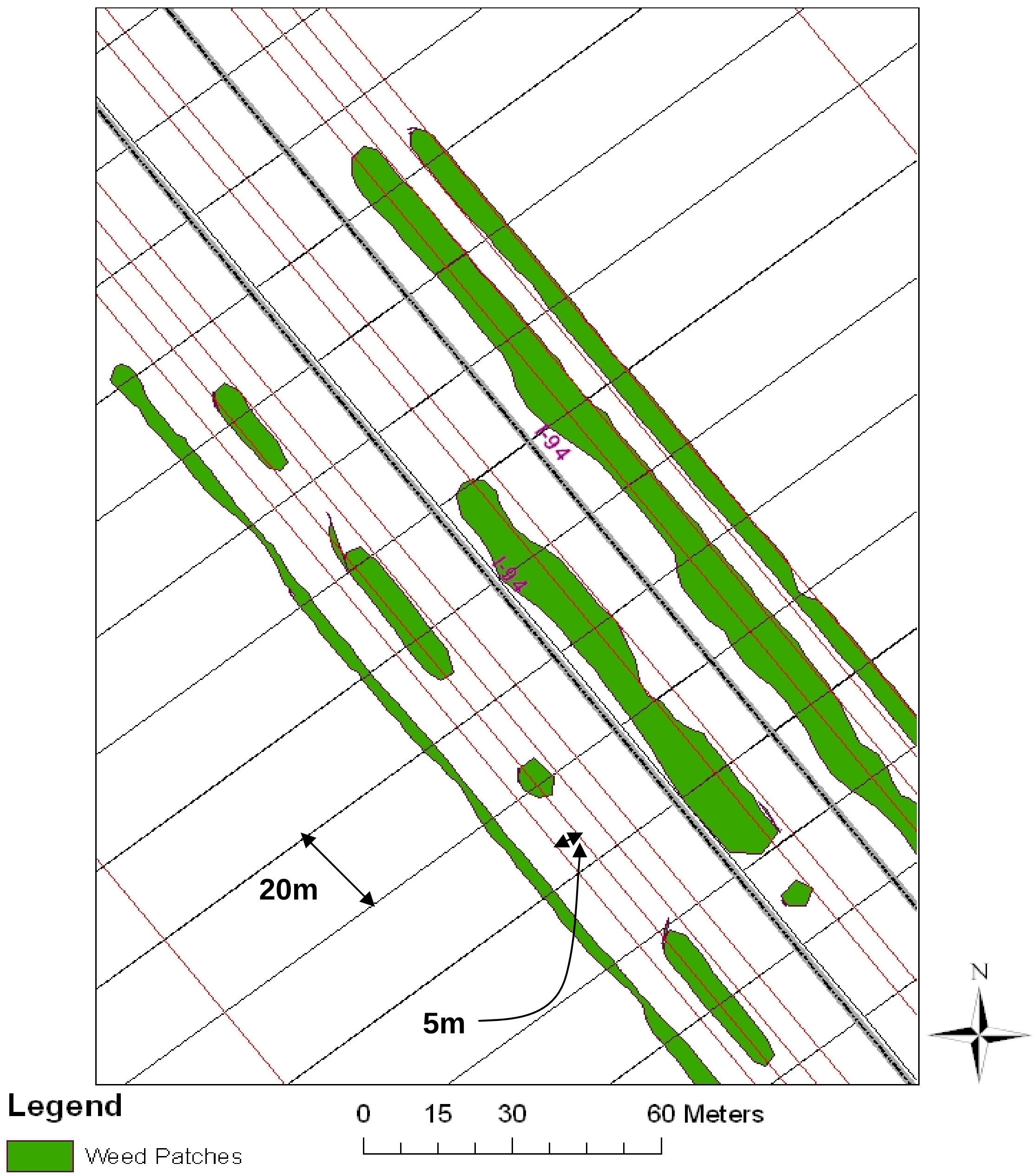


Figure 4.8b: Illustration of sectioning of roadway right-of-way and weed patches into 20 m segment units further sectioned at 5 m intervals across ROWs

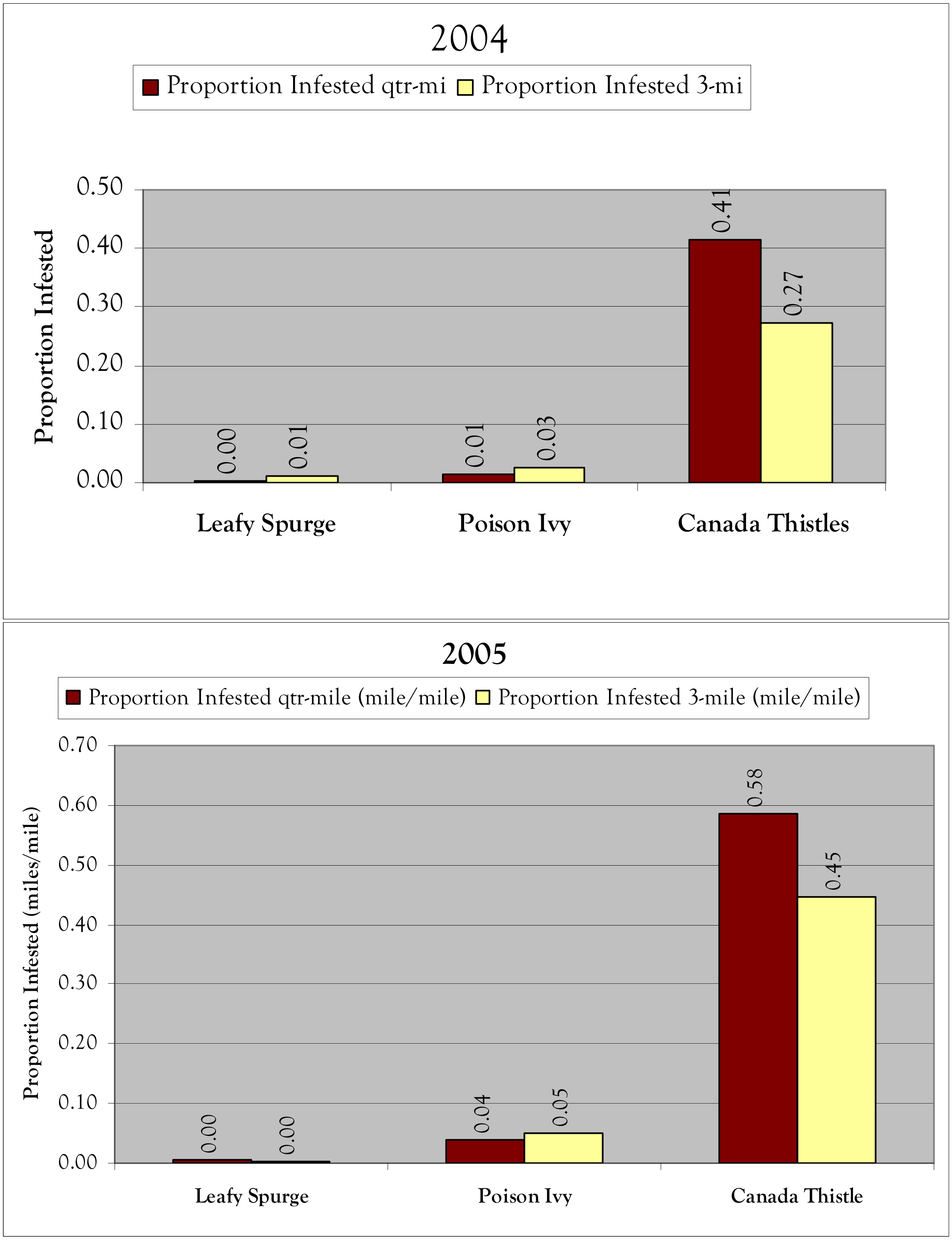
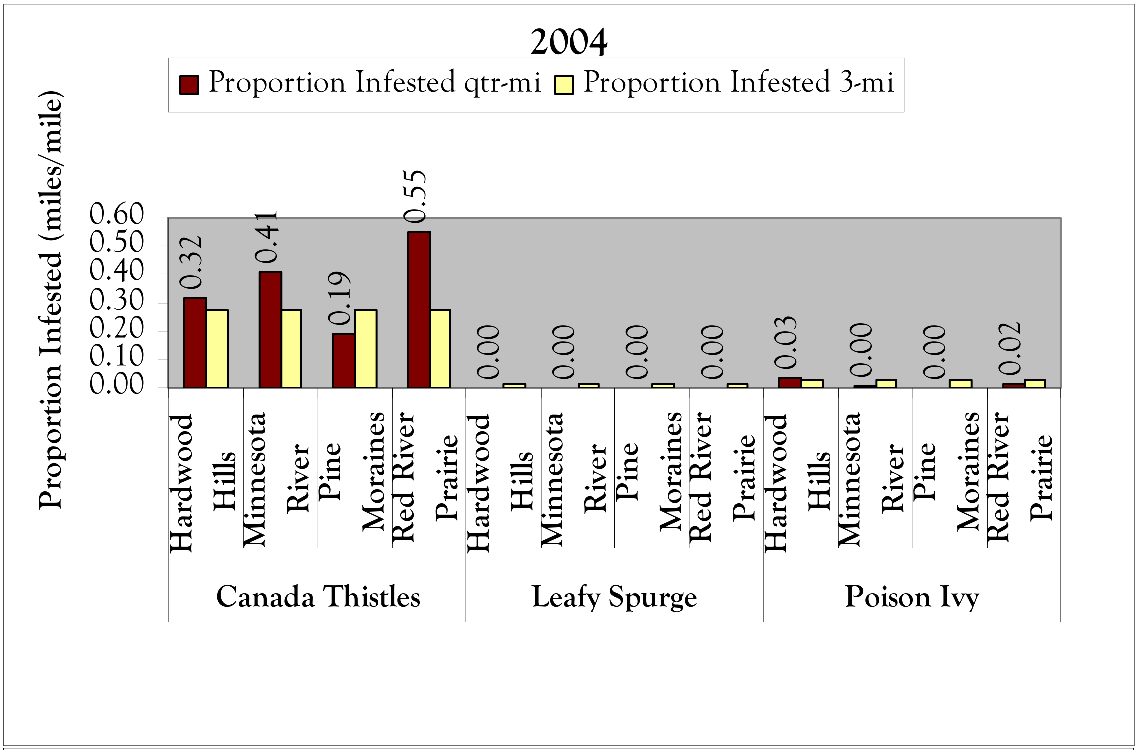


Figure 4.9: Proportion of surveyed road edge miles infested by Canada thistle, leafy spurge and poison ivy in District 4 based on 3-mile and ¼-mile surveys in 2004 and 2005



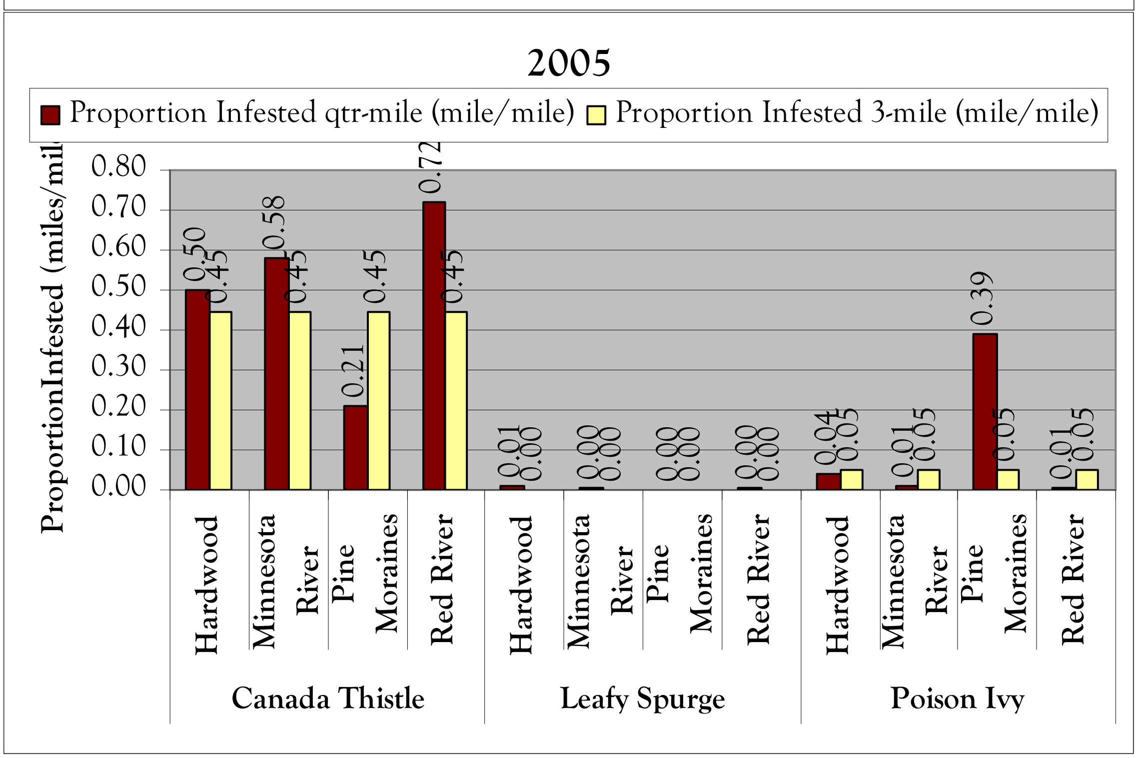


Figure 4.10: Proportion of surveyed road edge miles Infested by Canada thistle, leafy spurge and poison ivy in ecological zones based on 3-mile (D4 grand mean) and ¼-mile surveys in 2004 and 2005

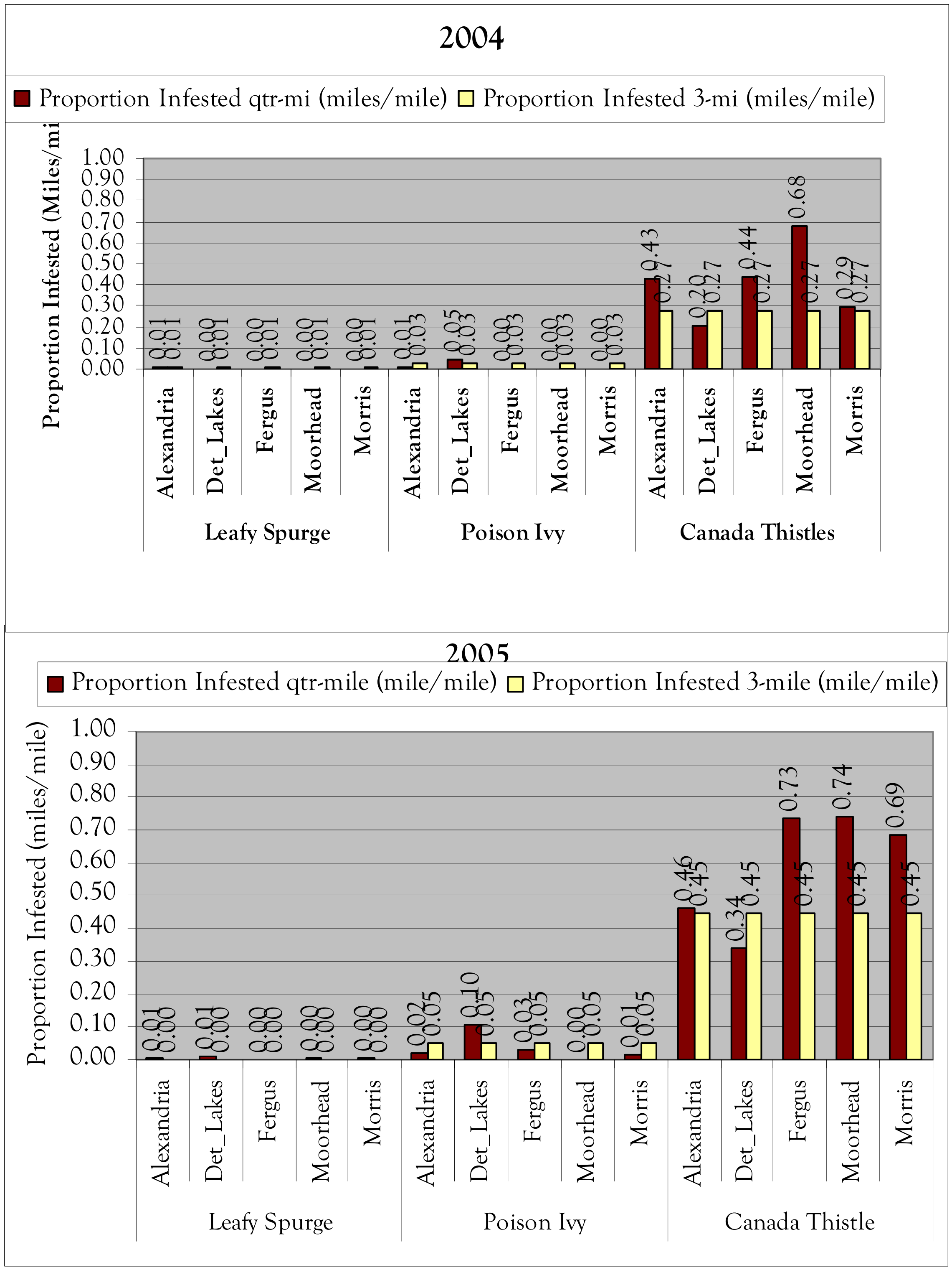


Figure 4.11a: Proportion of surveyed road edge miles Infested by Canada thistle, leafy spurge and poison ivy in management sub-districts based on 3-mile (D4 grand mean) and ¼-mile surveys in 2004 and 2005

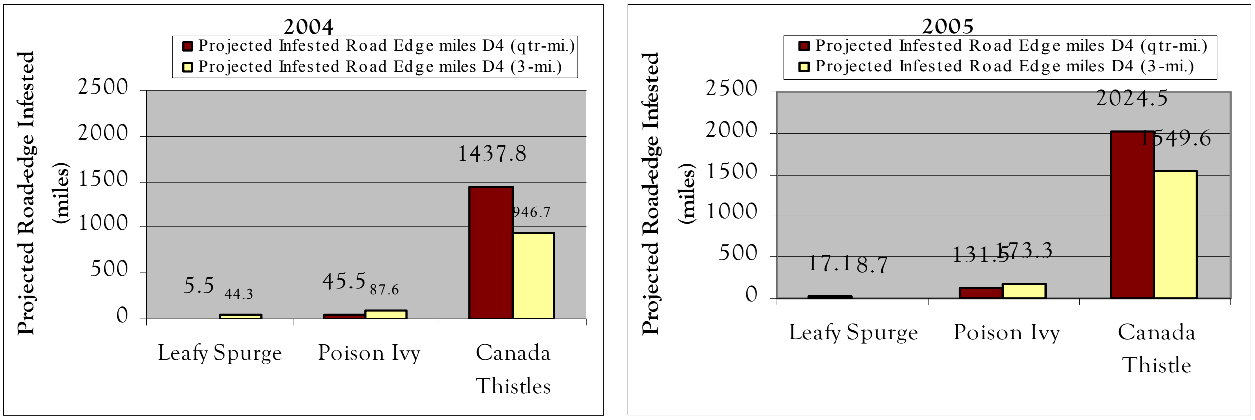


Figure 4.11b: Predicted total road edge miles infested by Canada thistle, leafy spurge and poison ivy in District 4 based on 3-mile and ¼-mile surveys in 2004 (L) and 2005 (R)

4.7 Determination of Infestation per landscape position

Infestations were evaluated over landscape positions across roadside ROWs. These positions were taken arbitrarily as 15 feet wide consecutive strips running parallel to highways, width measured initiated at edge of pavement (figures 4.6b and 10). These strips correspond approximately to sections of boom sprayer commonly used by the Minnesota Department of Transportation in roadside vegetation management. Results of analysis of data are presented in figures 4.9b and 4.11. Based on data recorded for the surveyed areas, total acres infested within a strip were determined. Mean infested acres-per-mile were then evaluated for each of the three regional levels.

Results of conducted data analysis showed high variations in levels of infestations across landscape positions. Infestations were consistently higher in positions close to roadways, declining towards the fence-line. These trends were consistent in both years' data for all ecological zones and management sub-districts of the study area.

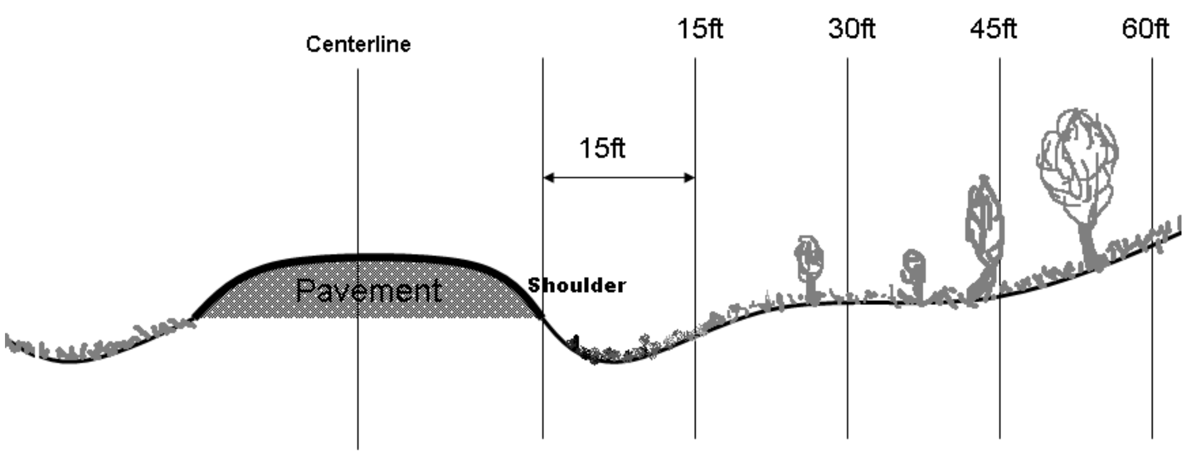


Figure 12: Illustration of partitioning of highways ROWs into 15 ft (5m) strips for determination of weed occurrence across landscape positions

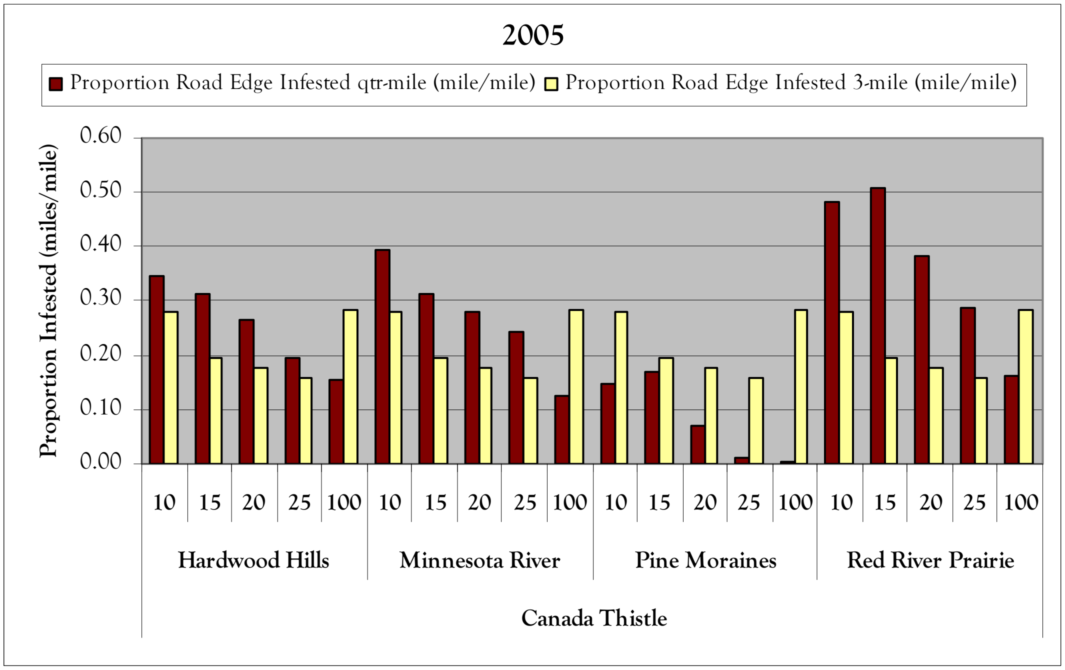


Figure 4.13a: Proportion of surveyed road edge miles Infested by Canada thistle in landscape positions (5, 10, 15… m from edge of pavement) of Ecological Zones based on 3-mile (D4 grand mean) and ¼-mile surveys in 2005

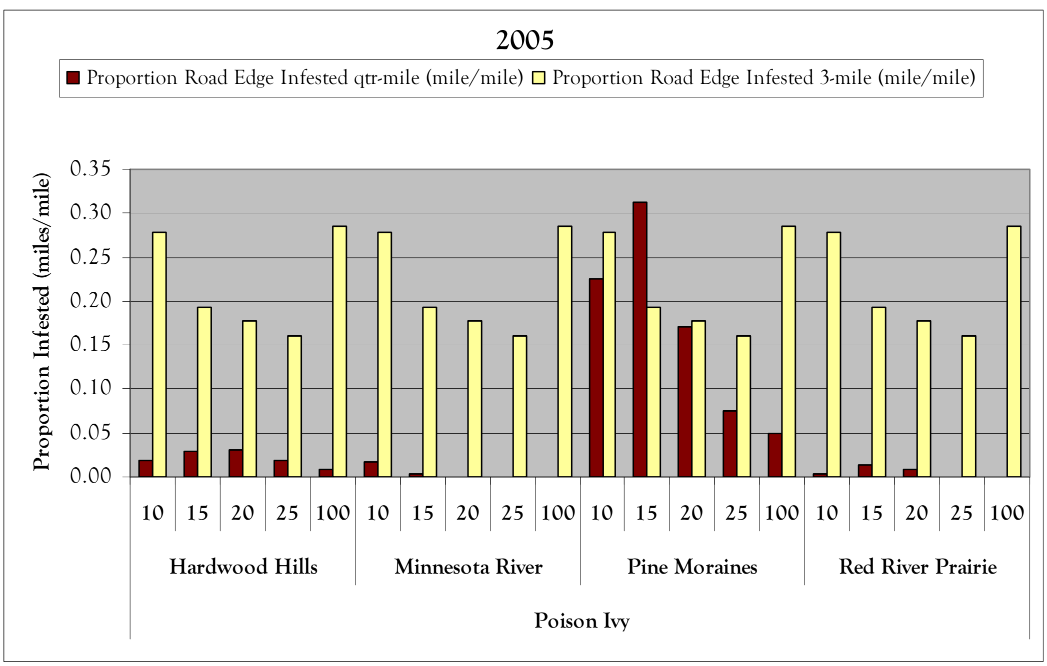


Figure 4.13b: Proportion of surveyed road edge miles Infested by poison ivy in landscape positions (5, 10, 15… m from edge of pavement) of ecological zones based on 3-mile (D4 grand mean) and ¼-mile surveys in 2005

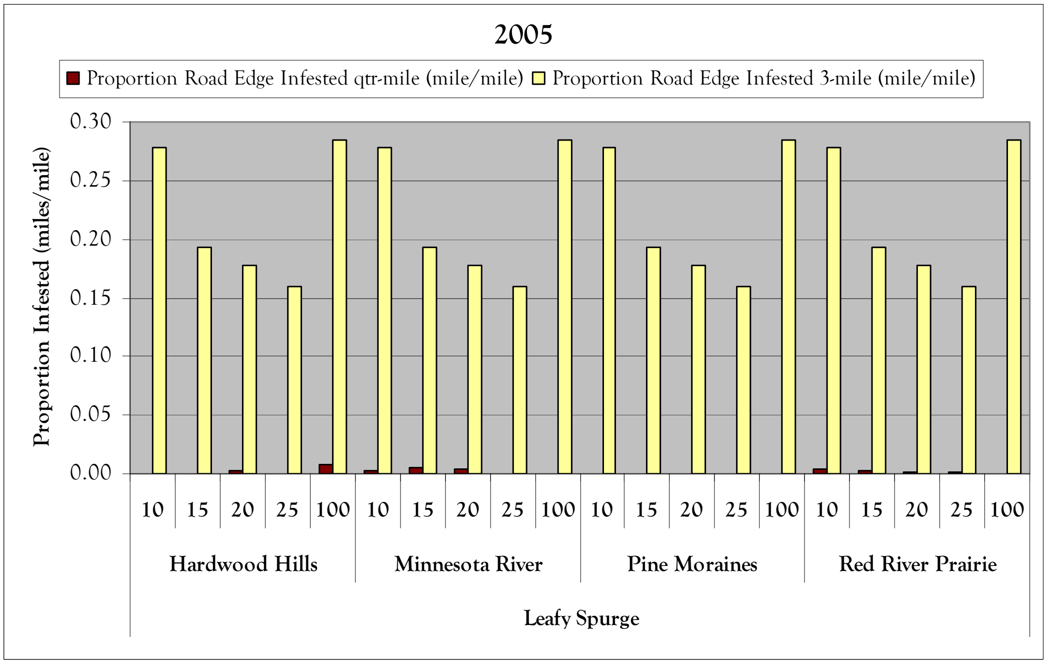


Figure 4.13c: Proportion of surveyed road edge miles infested by leafy spurge in landscape positions (5, 10, 15… m from edge of pavement) of ecological zones based on 3-mile (D4 grand mean) and ¼-mile surveys in 2005

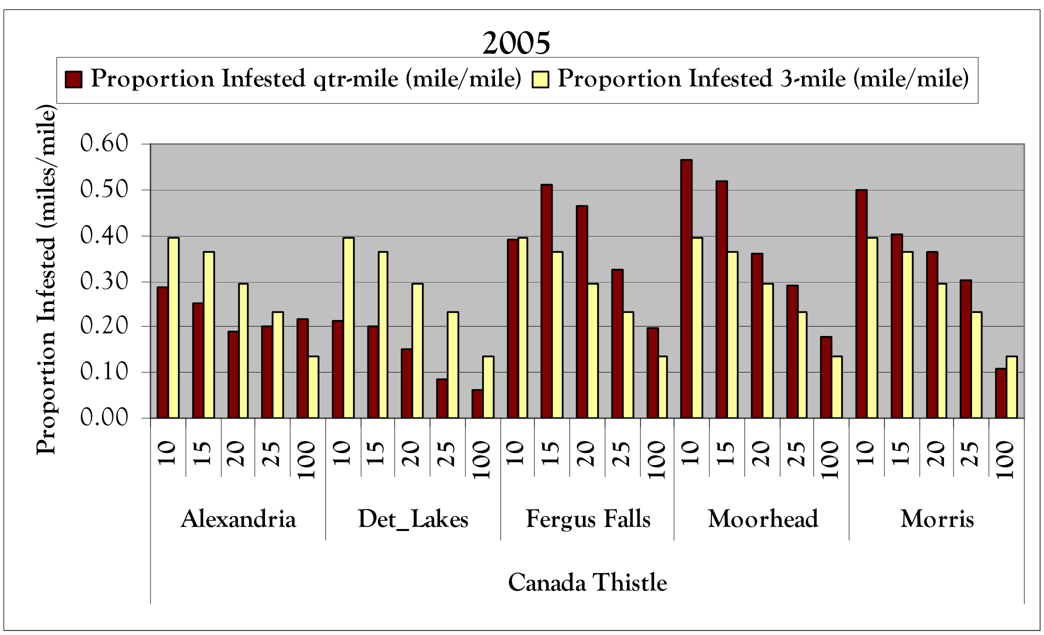


Figure 4.14a: Proportion of surveyed road edge miles infested by Canada thistle in landscape positions of management sub-districts based on 3-mile (D4 grand mean) and ¼-mile surveys in 2005

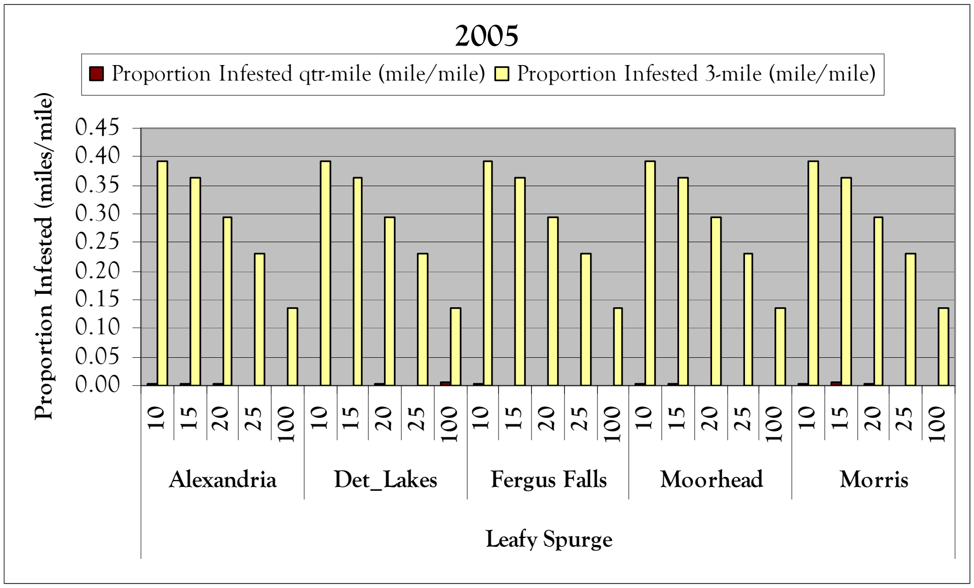


Figure 4.14b: Proportion of surveyed road edge miles infested by leafy spurge in landscape positions (5, 10, 15… m from edge of pavement) of management sub-districts based on 3-mile (D4 grand mean) and ¼-mile surveys in 2005

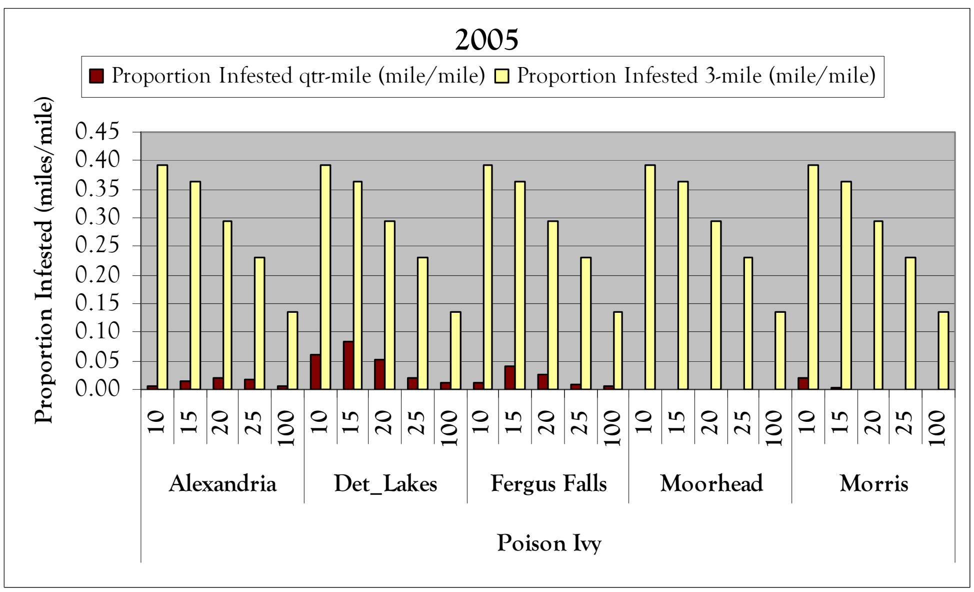
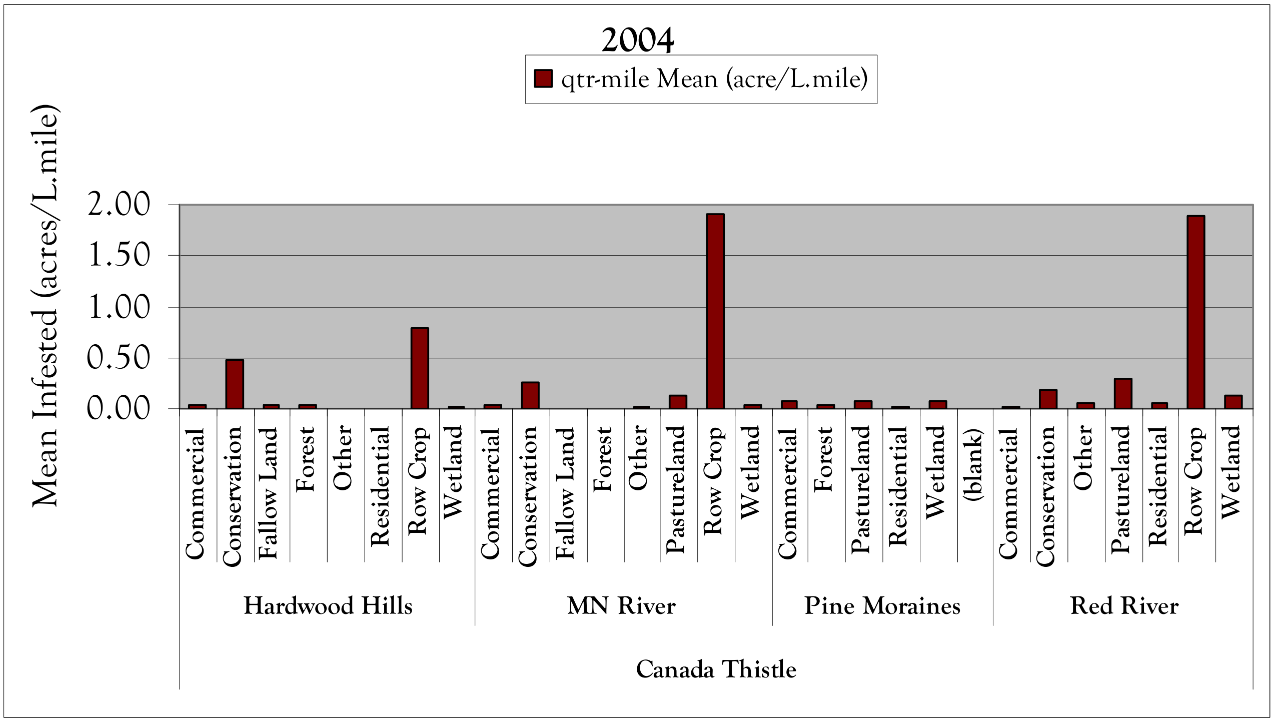


Figure 4.14c: Proportion of surveyed road edge miles infested by poison ivy in landscape positions of management Sub-districts based on 3-mile (D4 grand mean) and ¼-mile surveys in 2005

Information provided from these determinations can be valuable to weed managers in their planning for acquisition of control measures. Approximate total miles infested by each species, together with total acres, are valuable datasets in making management decisions. This will improve prediction accuracy of quantities and costs to be incurred in future weed management activities.

4.8 Influence of adjacent land-use on infestation by given weed species

Dynamics of weed population a given location may be influenced by cover type in adjacent areas. This may partially be due to the ease seeds from an infested site reaching un-infected sites they are in close proximity to. This theory was tested in the current project, with the analysis of data recorded in sampling surveys. Results show generally higher levels of infestations in areas adjacent to row crop cover type (figures 4.13 – 4.16), Row crop cover type occurred in a significantly larger area than all the other cover types. in the district. It was also noted that density (mean acres-per-mile) of Canada thistle and leafy spurge infestations were highest adjacent to this land cover type. However, this trend was not observed for poison ivy which occurred prevalently adjacent to forest and conservation cover types.



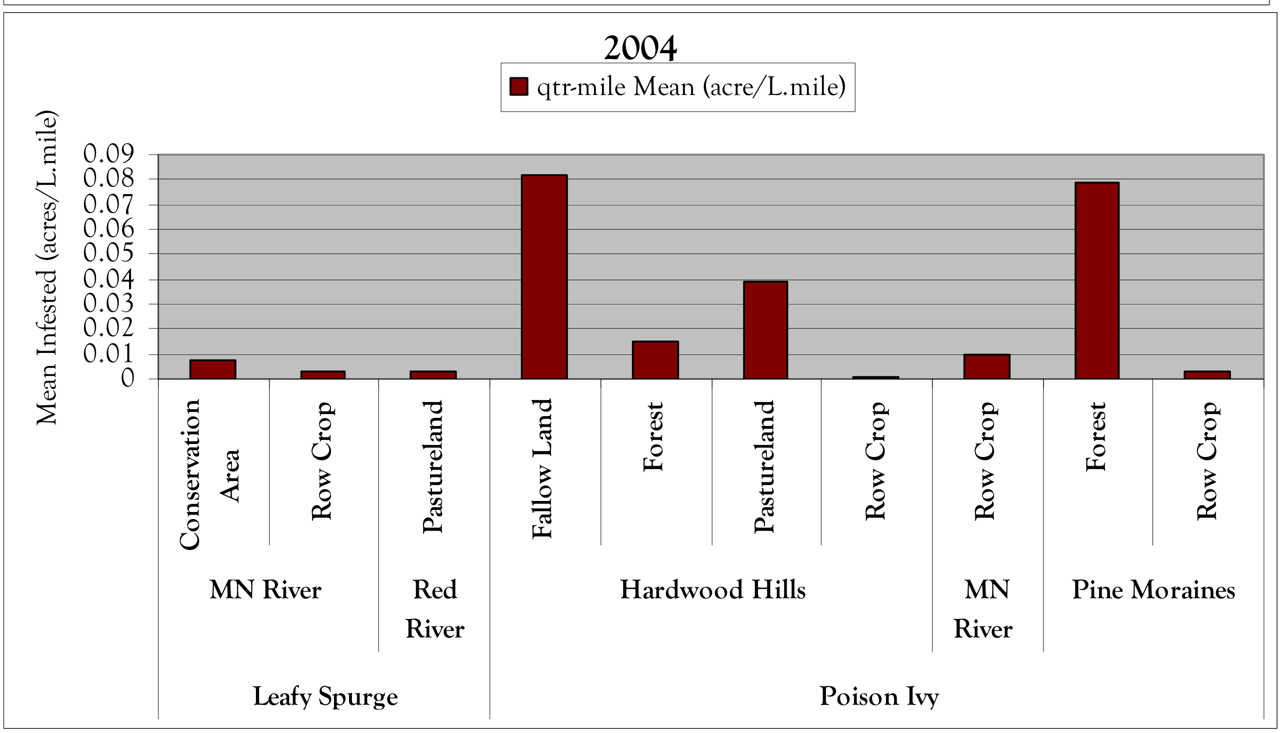
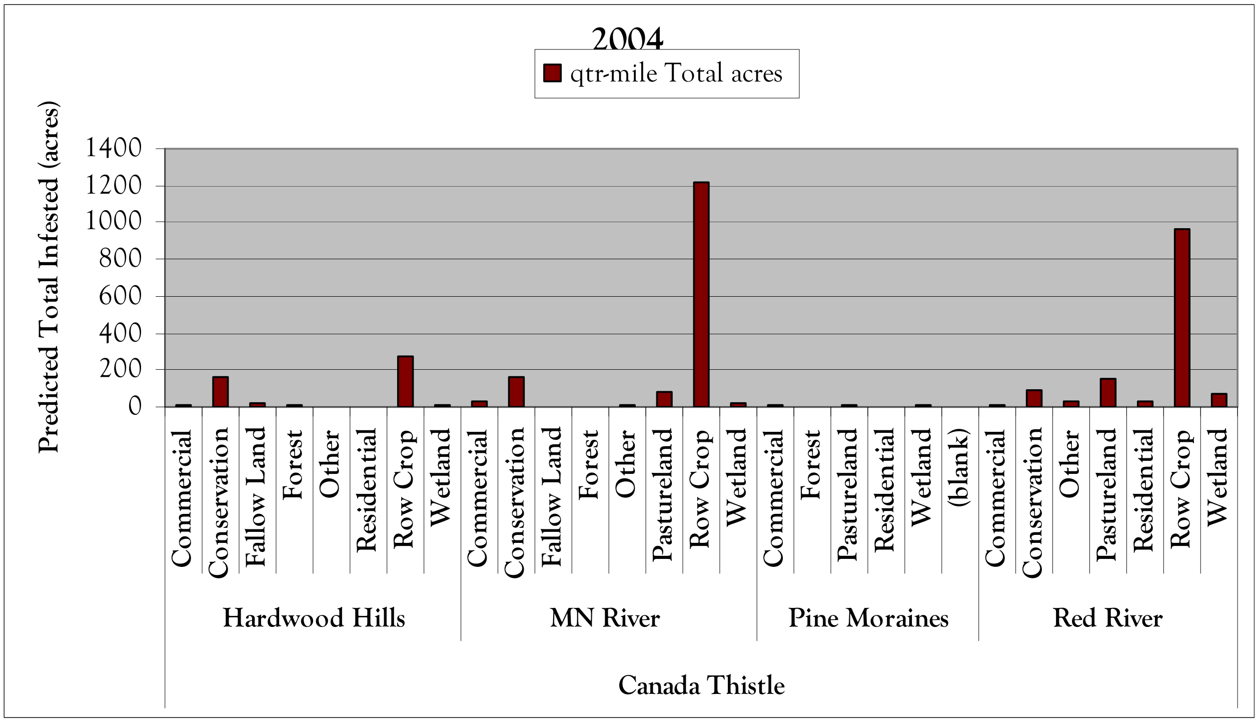


Figure 4.15: Relationship between adjacent land use and mean area infested by Canada thistle, leafy spurge and poison ivy in ecological zones based on ¼-mile surveys of 2004



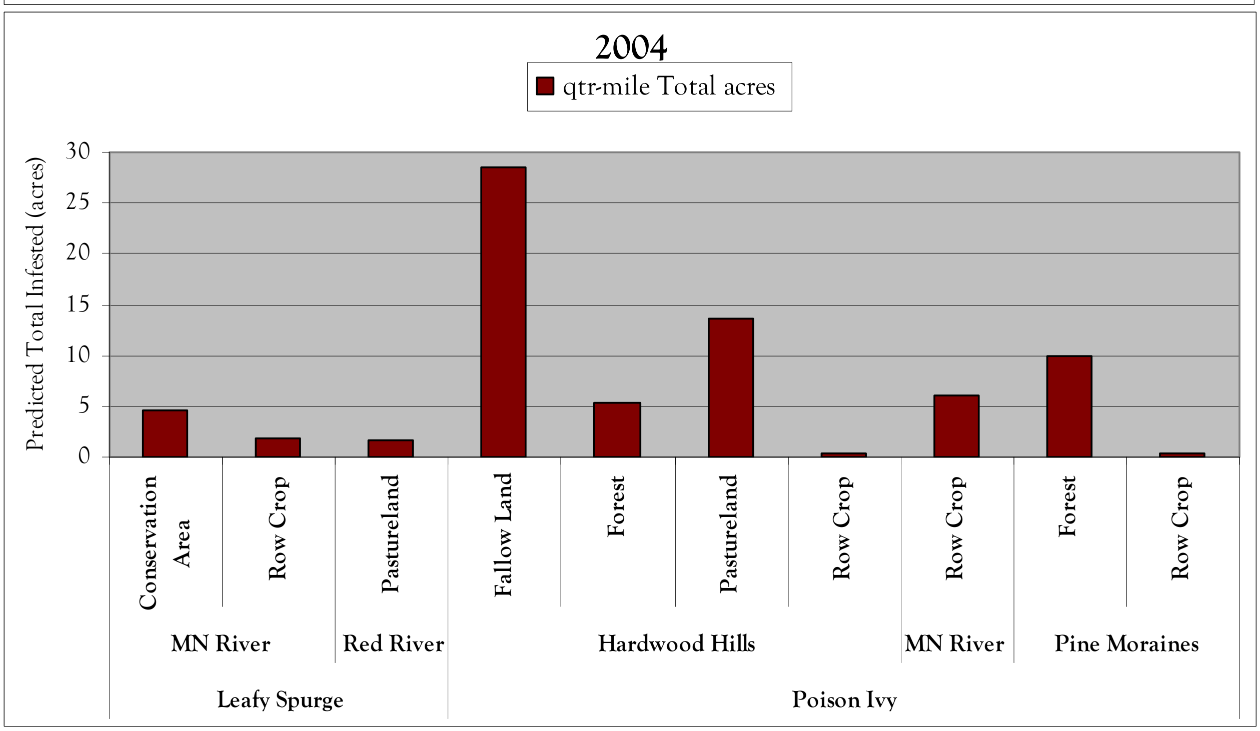


Figure 4.16: Relationship between adjacent land use and predicted total area infested by Canada thistle, leafy spurge and poison ivy in ecological zones based on ¼-mile surveys of 2004

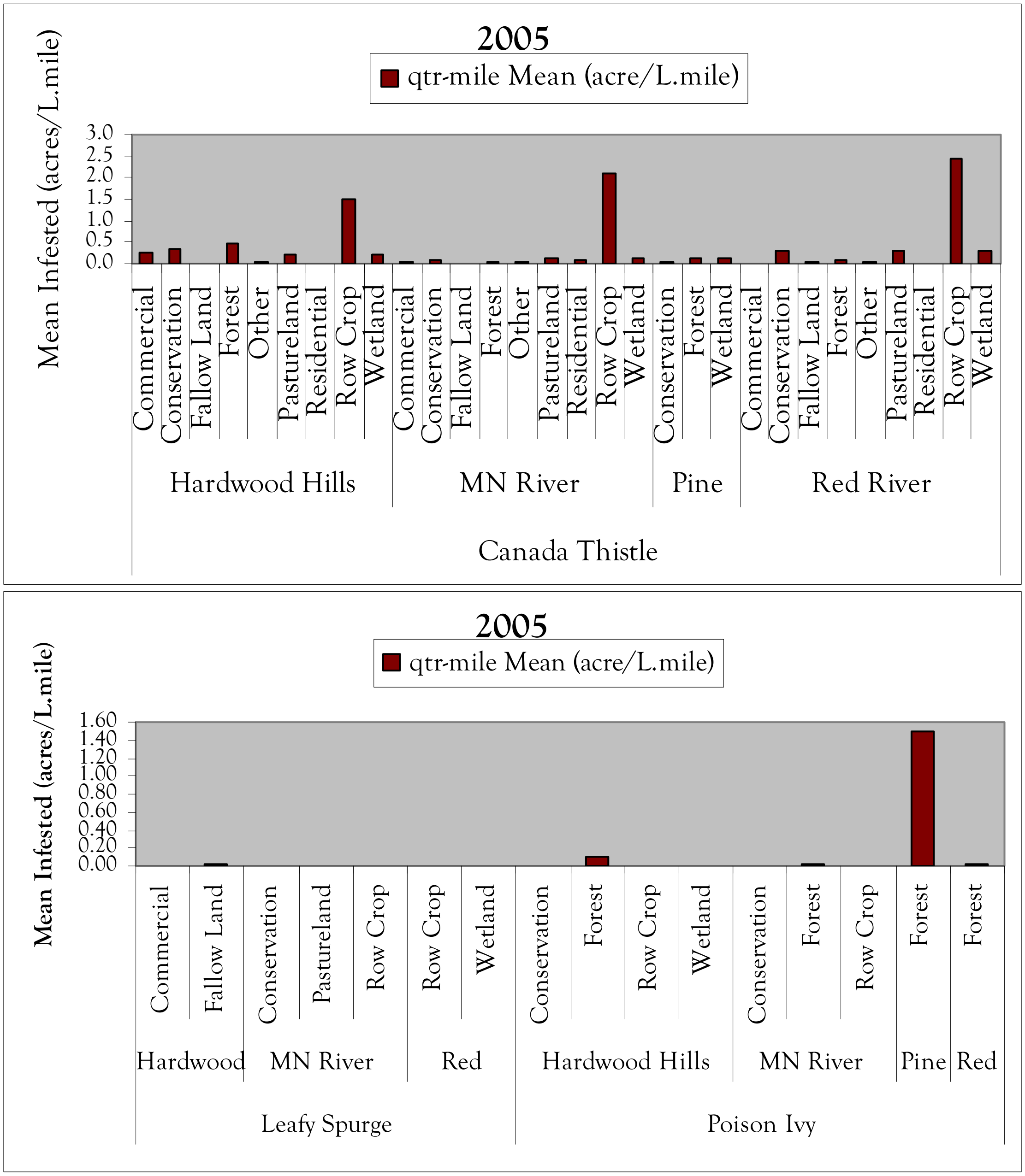


Figure 4.17a: Relationship between adjacent land use and mean area infested by Canada thistle, leafy spurge and poison ivy in ecological zones based on ¼-mile surveys of 2005

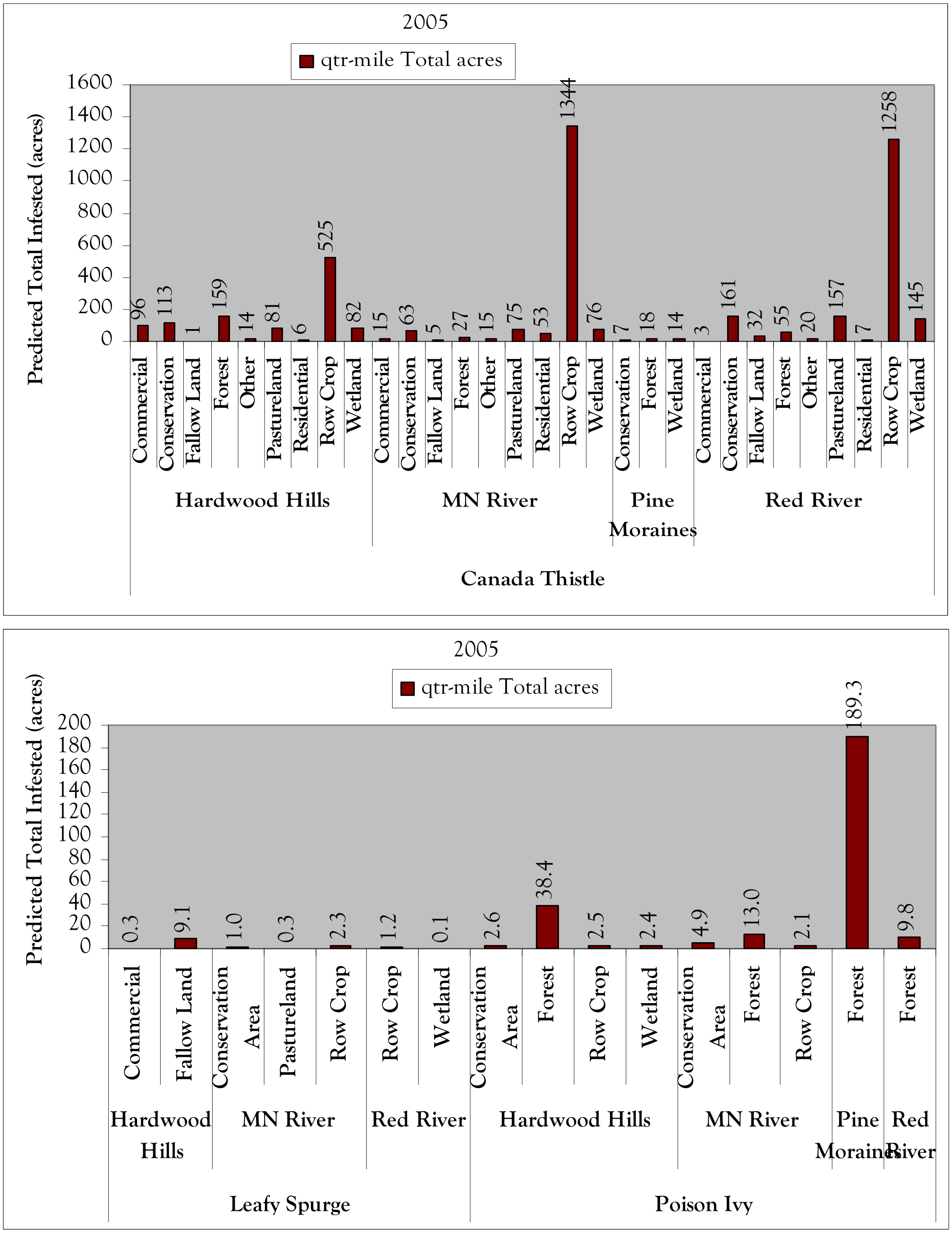


Figure 4.17b: Relations between adjacent land use and predicted total area infested by Canada thistle, leafy spurge and poison ivy in ecological zones based on ¼-mile surveys, 2005

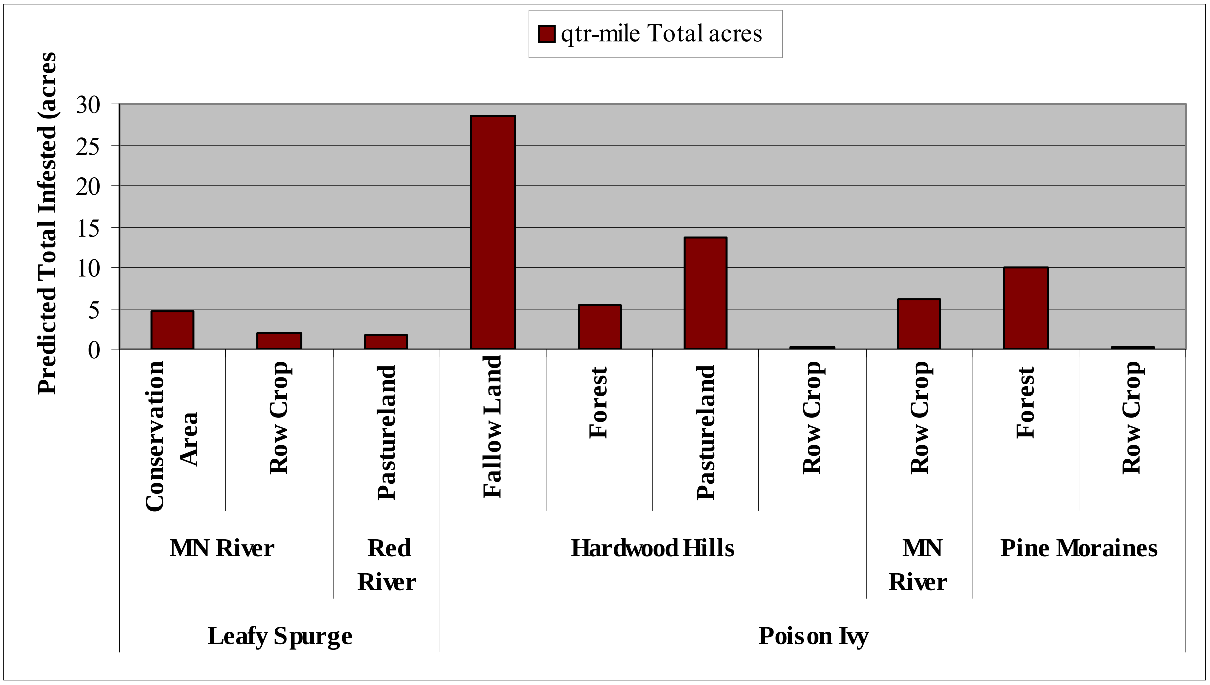


Figure 4.18: Relations between adjacent land use and predicted total area infested by Canada thistle, leafy spurge and poison ivy in ecological zones based on ¼-mile surveys, 2004

4.9 Discussions

The results of analysis of mean infested evaluated from data recorded in surveys using the 3-mile and quarter-mile sampling designs showed mixed results. Significant differences were observed between means at ecological zones, and management-sub-district levels. Generally, the quarter-mile design acre-per-mile values showed significant difference across ecological regions and management sub-districts. In summary:

- The obtained mean infested acres-per-mile for the three noxious weeds obtained in application of the two survey methods were not significantly different.. However, the variances of the quarter-mile survey means were much lower than for the 3-mile means, suggesting higher precision in estimations of weed populations using quarter-mile sampling designs.
- For some of the species, acres-per-mile differed significantly among ecological zones and management sub-districts. These results justify stratification by ecological zones during design and selection of samples for weed surveys.
- If observed differences in weed abundance among ecological zones are verified, then regional management strategies might take into consideration these differences in prioritizing management resources within Mn/DOT District 4.
- Density of Canada thistle was greatest adjacent to the pavement, and diminished with distance. The reason for this pattern is unknown at present. This could be due to traffic as

spreading agent; mower or sprayers as spreading agents; more intensive control next to farmers' fields; generally, there is usually less moisture stress due to runoff from roadway.

Chapter 5

Optimum Sample Size and Number for Weed Survey

5.1 Introduction

Sampling surveys are valuable tools for evaluating populations over large areas using information recorded in observations made at a few representative sites. Beginning 2000, District 4 of the Minnesota Department of Transportation initiated surveys for three problem weed species (Canada thistle, poison ivy, and leafy spurge) in rights-of-way of the highways under its jurisdiction. The surveys adopted strategies employing a small number of sampling sites at fixed locations. The sample, comprising of seven, 3- mile segments, was selected following procedures developed by Mn/DOT District 4 (Mn/DOT Office, Alexandria; personal communication). The current project has attempted to address questions regarding validity of this sampling procedure in representing the character of weed infestations in District 4.

The correlation between the number and size of sampling units, and precision of population estimation is well documented. In field trials to predict forage production, (Waddington and Cooke, 1971) observed that the number of sites needed to estimate a 95% confidence interval were fewer with replications. According to (Lodge, 1976) standard errors, for different levels of sampling with and without stratification of the plot, can be used to determine the sampling intensity needed to achieve an acceptable standard error for each mean basal cover. Increasing the number of points sampled over the surveyed area would result in a reduced standard error of the mean estimate of basal cover. Further, stratification of point samples appear to lower standard error and is more efficient in terms of field sampling time, than an increase in the number of points sampled.

The results obtained in the analysis of data from the current study show that a sampling process based on 100 0.25-mile sampling units distributed across the ecological regions in Mn/DOT District 4 is more precise prediction of weed populations than the less intensive 7 3- mile sampling system. Further analysis has been conducted to determine if the 100 0.25-mile sampling system could be modified to reduce either the size or number of sampling units and still obtain the information necessary for making relevant and accurate weed management decisions in the district. This chapter discusses procedures employed in the determination of optimum sample size and number to be used in future surveys of highway rights-of-way by MnDOT District 4.

5.2 Optimum number and size of samples

In this phase of the project, we have developed procedures for to aid personnel responsible for decisions of weed management to determine the appropriate size and number of the sampling units to be used in estimating weed populations, with lower costs and higher precisions. This is necessary for managers to make informed decisions on weed management in the Mn/DOT District 4. Data collected from the 2004 and 2005 surveys, comprising of 200 0.25- mile sampling sites, was analyzed. One of the goals of the analysis was to facilitate estimations of weed populations in the Mn/DOT District 4

5.2.1 Number of sampling sites

In this analysis, the decision on the optimum sample number has been based on sampling precision, which is established gauged on the size of the obtained standard error of the means. A standard error of the mean of approximately 20% was deemed reasonable to satisfy the accuracy required by Mn/DOT in these determinations. While a higher level of precision would be preferred, the high costs and sampling time associated with the precision would be prohibitive.

We have developed tools in MS Excel® to be used in the selection, by trial and error, of appropriate number of sampling sites. These tools (worksheets) enable a decision maker to determine the optimum sample number (New Total Segments in figure 5.2). An associated standard error of the mean is computed and displayed at another section (New ME/Mean %) of the same table. For accuracy, data from the LATEST previous surveys of the same area MUST be used in this analysis and selection of samples (statistics figure 5.1).

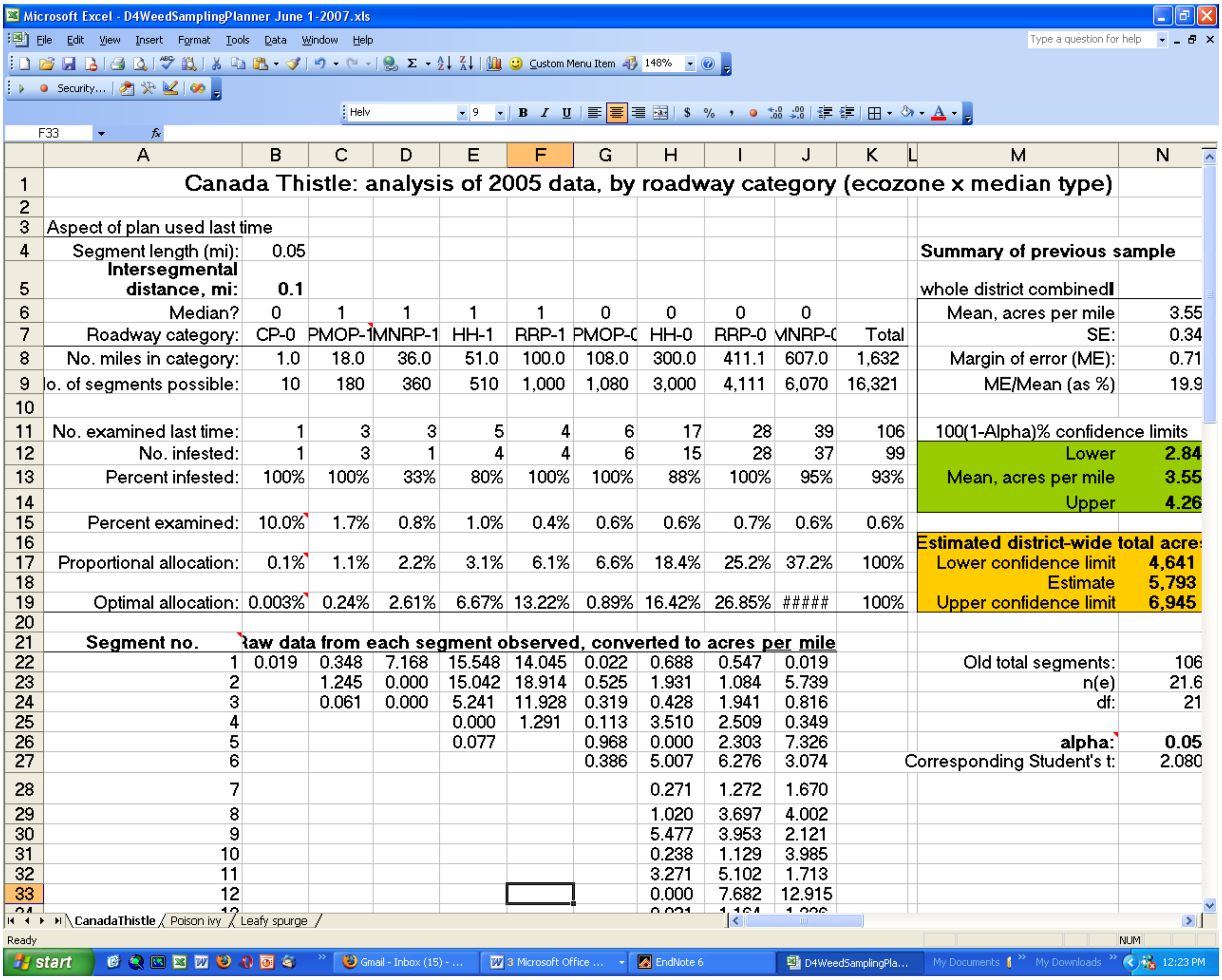
Figure 5. 2 illustrate results of selection of 100 0.25-mile sampling segments for adoption in the forthcoming surveys for Canada thistle infestation in District 4. The mean error (New ME%) for this sample number is 17.82, which is within acceptable limits (of 20%). The larger the sample number selected the lower standard error of measurement, hence the higher the achievable measurement precision. Due to large differences in character of infestation by different weed species, separate samples should be selected for each of the species for which surveys are to be conducted.

The lower left section of the figure 5.2 shows the number of sites selected for surveys at each of the 9 categories (ecological zone, type of road) in the district. Selction has been conducted, with number of sites being proportional to the number of highway miles in each category.

5.2.2 Size of sampling sites

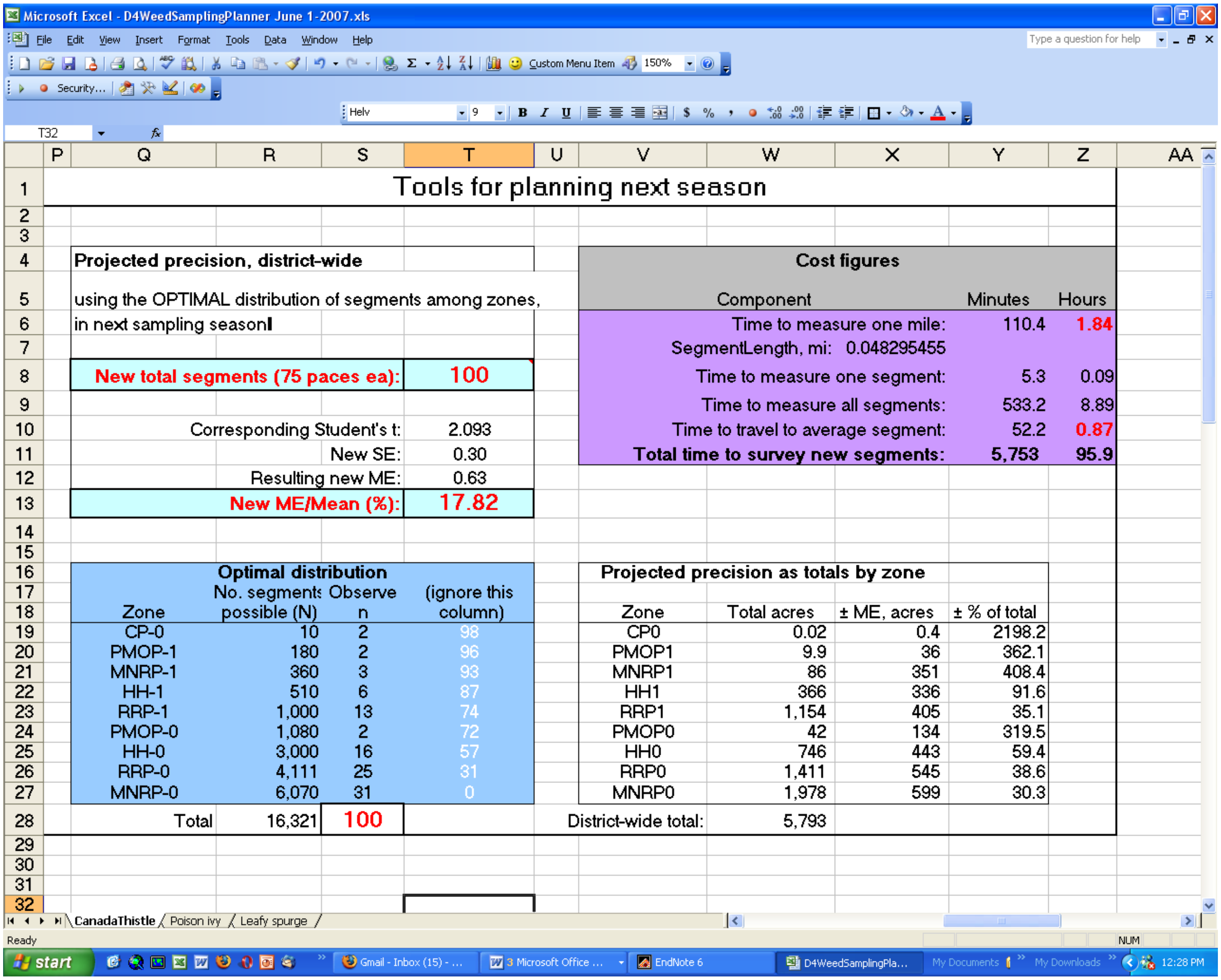
An analysis of data was conducted to investigate if the ¼-mile survey method could be modified to reduce the size of the sampling units and still obtain information necessary for making accurate relevant decisions on weed management in the district. In this effort, the data obtained from surveys using 3-mi and ¼-mi segments were re-sampled using MS EXCEL ® tools. The 3-mi. data were re-sampled into three sub-segment sizes: 0.1-, 0.5-, and 1-mi. sub-segment lengths, while the ¼-mi. data were re-sampled into 0.004-, 0.024-, and 0.044-mi. lengths. The different segment lengths were compared in a test of population estimation efficiency over larger areas. Efficiency tests were based on relative net precision (RNP) of each size. The RNP of segment lengths were evaluated from the total cost of surveying the segment, and variance of estimation [(Segment length/Cost of survey) * (Segment length / Variance)]. The results showed a consistent increase in RNP values with decrease in segment length (Tables 5.3-5.5). The trends held for both the 3-mi. and ¼-mi. segments' data, for all weed species except leafy spurge (minor weed). The deviancy from the trend was attributed to the low occurrence and distribution of leafy spurge in ecological zones of the study area. This was a minor problem species (Table 5.5), occurring in few sites across the study area.

High RNP attributed to a segment length implies a higher accuracy of estimation of infestations in larger areas by the surveys using the sample unit. In all cases where judgments were possible, the shortest segment length (0.004 mile length), had the highest relative precision, followed by the 0.024 mile (Table 5.3 and 5.4). Based on these results, the optimum size sampling unit was determined to be the shortest one. This unit would however, due to the minimal length, be suitable for surveys which require recording of the absence-presence data only, and not for mapping.



	A	B	C	D	E	F	G	H	I	J	K	M	N
1	Canada Thistle: analysis of 2005 data, by roadway category (ecozone x median type)												
2													
3	Aspect of plan used last time												
4	Segment length (mi):	0.05										Summary of previous sample	
5	Intersegmental distance, mi:	0.1										whole district combined	
6	Median?	0	1	1	1	1	0	0	0	0		Mean, acres per mile	3.55
7	Roadway category:	CP-0	PMOP-1	MNRP-1	HH-1	RRP-1	PMOP-(	HH-0	RRP-0	MNRP-(	Total	SE:	0.34
8	No. miles in category:	1.0	18.0	36.0	51.0	100.0	108.0	300.0	411.1	607.0	1,632	Margin of error (ME):	0.71
9	lo. of segments possible:	10	180	360	510	1,000	1,080	3,000	4,111	6,070	16,321	ME/Mean (as %)	19.9
10													
11	No. examined last time:	1	3	3	5	4	6	17	28	39	106	100(1-Alpha)% confidence limits	
12	No. infested:	1	3	1	4	4	6	15	28	37	99	Lower	2.84
13	Percent infested:	100%	100%	33%	80%	100%	100%	88%	100%	95%	93%	Mean, acres per mile	3.55
14												Upper	4.26
15	Percent examined:	10.0%	1.7%	0.8%	1.0%	0.4%	0.6%	0.6%	0.7%	0.6%	0.6%		
16												Estimated district-wide total acre	
17	Proportional allocation:	0.1%	1.1%	2.2%	3.1%	6.1%	6.6%	18.4%	25.2%	37.2%	100%	Lower confidence limit	4,641
18												Estimate	5,793
19	Optimal allocation:	0.003%	0.24%	2.61%	6.67%	13.22%	0.89%	16.42%	26.85%	#####	100%	Upper confidence limit	6,945
20													
21	Segment no.	Raw data from each segment observed, converted to acres per mile											
22	1	0.019	0.348	7.168	15.548	14.045	0.022	0.688	0.547	0.019		Old total segments:	106
23	2		1.245	0.000	15.042	18.914	0.525	1.931	1.084	5.739		n(e)	21.6
24	3		0.061	0.000	5.241	11.928	0.319	0.428	1.941	0.816		df:	21
25	4				0.000	1.291	0.113	3.510	2.509	0.349			
26	5				0.077		0.968	0.000	2.303	7.326		alpha:	0.05
27	6						0.386	5.007	6.276	3.074		Corresponding Student's t:	2.080
28	7							0.271	1.272	1.670			
29	8							1.020	3.697	4.002			
30	9							5.477	3.953	2.121			
31	10							0.238	1.129	3.985			
32	11							3.271	5.102	1.713			
33	12							0.000	7.682	12.915			

Figure 5.1: Screen shot of spreadsheet "WeedSamplingPlanner.xls" applied in selection of number of samples (at X), and the corresponding measurement error (at Y) for adoption in surveying for Canada thistle in highways rights-of-way, 2005



Microsoft Excel - D4WeedSamplingPlanner June 1-2007.xls

Tools for planning next season

Projected precision, district-wide

using the OPTIMAL distribution of segments among zones, in next sampling season

New total segments (75 paces ea):	**100**
Corresponding Student's t:	2.093
New SE:	0.30
Resulting new ME:	0.63
New ME/Mean (%):	**17.82**

Cost figures

Component	Minutes	Hours
Time to measure one mile:	110.4	1.84
SegmentLength, mi: 0.048295455		
Time to measure one segment:	5.3	0.09
Time to measure all segments:	533.2	8.89
Time to travel to average segment:	52.2	0.87
Total time to survey new segments:	**5,753**	**95.9**

Optimal distribution

Zone	No. segments possible (N)	Observe n	(ignore this column)
CP-0	10	2	98
PMOP-1	180	2	96
MNRP-1	360	3	93
HH-1	510	6	87
RRP-1	1,000	13	74
PMOP-0	1,080	2	72
HH-0	3,000	16	57
RRP-0	4,111	25	31
MNRP-0	6,070	31	0
Total	16,321	100	

Projected precision as totals by zone

Zone	Total acres	± ME, acres	± % of total
CP0	0.02	0.4	2198.2
PMOP1	9.9	36	362.1
MNRP1	86	351	408.4
HH1	366	336	91.6
RRP1	1,154	405	35.1
PMOP0	42	134	319.5
HH0	746	443	59.4
RRP0	1,411	545	38.6
MNRP0	1,978	599	30.3
District-wide total:	5,793		

CanadaThistle / Poison ivy / Leafy spurge

Figure 5.2: Screen shot of spreadsheet “WeedSamplingPlanner.xls” applied in selection of number of samples (at X), and the corresponding measurement error (at Y) for adoption in surveying for Canada thistle in highways rights-of-way, 2005

Table 5.3: Summary statistics and relative net precision (RNP) of different subsegment lengths for estimating acres of Canada thistle per road mile, based on N = 5,000 re-samplings of ~100 original 1/4 mi segments, grouped by ecoregion in District 4

	CP-0		**HH-0**		**HH-1**		**MNRP-0**		**MNRP-1**		**PMOP-0**		**PMOP-1**		**RRP-0**		**RRP-1**	
Statistic	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
No. sampled:	0	1	13	17	3	5	28	39	7	3	10	6	3	0	27	28	7	4
No. infested:	—	1	11	15	3	4	25	37	7	1	8	6	3	—	26	28	6	4
Acres per mile:	—	0.02	0.75	1.99	2.98	5.75	1.43	2.61	4.07	1.91	0.13	0.31	0.55	—	1.67	2.75	4.75	9.24
Variance:	—	—	1.46	5.45	13.14	38.02	1.91	5.27	3.44	10.96	0.07	0.07	0.38	—	2.19	7.15	12.23	35.38
Subsegment																		
length (mi)																		
0.004	—	—	**63.1**	**16.3**	**7.3**	**3.7**	**28.1**	**17.8**	**14.8**	**16.5**	**333.1**	**287.9**	**120.3**	**—**	**34.2**	**15.8**	**6.2**	**3.7**
0.024	—	—	14.2	3.1	1.4	0.7	5.7	3.4	3.1	2.8	71.4	114.9	34.9	—	6.9	3.0	1.1	0.7
0.044	—	—	8.9	1.9	0.7	0.4	3.7	2.1	1.9	1.6	64.0	74.8	22.5	—	4.5	1.8	0.7	0.4
0.25 (full)	—	—	0.37	0.10	0.04	0.01	0.28	0.10	0.16	0.05	7.40	7.45	1.42	—	0.25	0.08	0.04	0.02

Table 5.4: Relative net precision (RNP) of different subsegment lengths for estimating acres of poison ivy

	CP-0		**HH-0**		**HH-1**		**MNRP-0**		**MNRP-1**		**PMOP-0**		**PMOP-1**		**RRP-0**		**RRP-1**	
Statistic	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
No. sampled:	0	1	13	17	3	5	28	39	7	3	10	6	3	0	27	28	7	4
No. infested:	—	0	3	1	0	1	0	8	1	0	3	0	0	—	0	4	0	2
Acres per mile:	—	0.00	0.167	0.03	0.000	0.24	0.000	0.26	0.041	0.00	0.100	0.00	0.000	—	0.000	0.03	0.000	0.09
Variance:	—	—	0.356	0.0115	—	0.2788	—	1.2726	0.011	—	0.090	—	—	—	—	0.01398	—	0.01163
Subsegment																		
length (mi)																		
0.004	—	—	**340**	**314**	—	**716**	—	**2413**	**4084**	—	**940**	**17.2**	—	—	—	**4427**	—	—
0.024	—	—	65	77	—	139	—	449	759	—	170	2.9	—	—	—	797	—	
0.044	—	—	34	54	—	82	—	268	451	—	102	1.7	—	—	—	476	—	
0.25 (full)	—	—	1.5	—	—	1.95	—	0.43	47.3	—	6.02	—	—	—	—	—	—	46.7

Table 5.5: Relative net precision (RNP) of different sub-segment lengths for estimating acres of leafy spurge

	CP-0		**HH-0**		**HH-1**		**MNRP-0**		**MNRP-1**		**PMOP-0**		**PMOP-1**		**RRP-0**		**RRP-1**	
Statistic	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
No. sampled:	0	1	13	17	3	5	28	39	7	3	10	6	3	0	27	28	7	4
No. infested:	—	0	0	1	0	1	1	4	1	1	0	0	0	—	1	1	0	2
Acres per mile:	—	0	0.000	0.033	0.000	0.004	0.008	0.004	0.014	0.022	0.000	0	0.000	—	0.004	0.001	0.000	0.014
Variance:	—	—	—	0.0181	—	0.0001	0.0020	0.0002	0.0014	0.0015	—	—	—	—	4.4E-04	1.9E-05	—	0.001
Subsegment length (mi)																		
0.004	—	—	—	**1564**	—	**52017**	?	**19054**	?	?	—	—	—	—	**22275**	**170345**	—	**6457**
0.024	—	—	—	382	—	32051	?	7818	?	?	—	—	—	—	8701	144487	—	4428
0.044	—	—	—	284	—	30328	?	7940	?	?	—	—	—	—	6043	143811	—	4592
0.25 (full)	—	—	—	30	—	6403	279	2634	395	359	—	—	—	—	1245	27912	—	1020

5.3 Significance of infestation characteristics and sample selection for future surveys

As previously discussed, it is important that data applied in selection of sampling sites for future surveys be from the nearest immediate surveys of the same sites. Although sample selection methods were different between the two seasons, this analysis of data has attempted to allocate obtained infestation data to the 9 categories on the district. As reported earlier, the 2004's 100 0.25-mile segment samples were selected through complete random design, involving the population of 0.25-mile mile positions in District 4. In 2005 season, the sampling sites were selected through stratified random design; where sampling sites were optimally allocated among 9 strata (ecological zones and type-of-roadway combinations). District-wide mean areas infested by the 3 weed species evaluated from the data recorded in the two seasons are presented in tables 5.6 and 5.8. Application of the two years data in selection of sampling sites for the 2007 survey season (following procedures in sections 5.2.1 – 5.2.2, and figures 1 and 2) resulted in the allocations to the 9 strata presented in and tables 5.7 and 5.9. As can be observed, the number of sampling sites allocated per strata for Canada thistle (the most abundant species in district 4), were similar between years (Tables 5.7 and 5.9). However, allocations for the other rarer species were more erratic between years, and may be the result of higher sampling error for the low density weeds.

Since Canada thistle is the most abundant species in MnDOT District 4 our recommendation is that future weed surveys should be designed to most effectively manage this species.

5.3.1 Effect of sample size on sampling efficiency

To date, all of the district-wide statistics and allocations are based on the original 0.25-mile sample units. We have initiated further analysis to determine optimum sample size. In an initial analysis we found that a smaller segment length of 1/20 - mile was more efficient. If managers were to adopt the smaller size sampling unit distribution among the 9 strata, these should remain proportional to what was obtained with the 0.25 mile segments.

Further data analysis was conducted to test re-sampling for sizes smaller than 1/20-mile aimed at identifying more efficient sample size. A sample size, 1/250th –mile is being tested in surveys involving recording infestation data restricted to presence-absence of species. This sample size is allocated similar to the other sizes, maintaining distribution densities among the 9 strata.

Table 5.6: Summary statistics for measures of abundance of 3 weeds, in acres per mile of road, in each of 9 combinations of roadway types and ecological zones, sampled in 2004

Division+	N* (possible)	n	Canada thistle		Poison ivy		Leafy spurge	
			Mean	Variance	Mean	Variance	Mean	Variance
CP0	4	0	–	–	–	–	–	–
PM1	72	3	0.551	0.381	0.000	0.000	0.000	0.000
MNRP1	144	7	4.070	3.435	0.041	0.011	0.014	0.001
HWH1	204	3	2.984	13.141	0.000	0.000	0.000	0.000
RRP1	400	7	4.752	12.227	0.000	0.000	0.000	0.000
PM0	432	10	0.133	0.073	0.100	0.090	0.000	0.000
HWH0	1196	13	0.750	1.459	0.167	0.356	0.000	0.000
RRP0	1648	27	1.670	2.191	0.000	0.000	0.004	0.000
MNRP0	2420	28	1.384	1.582	0.000	0.000	0.008	0.002
∑:	6520	98						
	District-wide:		1.563		0.038		0.004	
	SE:		0.167		0.031		0.003	

+ - Division is ecozone, with roads subdivided into those without or with medians.

- - N is the total number of qtr-mi segments available in each zone.

Table 5.7: Optimal allocation of 100 qtr-mile segments among 9 subdivisions of District 4, to estimate abundance of each of three weed species (2004 data)

Division+	N* (possible)	No. segments to be examined next year		
		Canada thistle	Poison Ivy	Leafy spurge
CP0	4	2	2	2++
PM1	72	2	2	2
MNRP1	144	3	2	3
HWH1	204	7	2	2
RRP1	400	14	2	2
PM0	432	2	13	2
HWH0	1196	15	73	2
RRP0	1648	25	2	21
MNRP0	2420	31	2	64
Total:	6520	100	100	100

+ - Division is ecozone, with roads subdivided into those without or with medians.
* - N is the total number of qtr-mi segments available in each zone.
++ Value assigned using FUNCTION [=VLOOKUP(B2,LSAllocationTable,2)], B2 refers to the "N possible" value in same row

Table 5.8: Summary statistics for measures of abundance of 3 weeds, in acres per mile of road, in each of 9 combinations of roadway types and ecological zones, sampled in 2005

			Canada thistle		Poison ivy		Leafy spurge	
Division	N (possible)	n	Mean	Variance	Mean	Variance	Mean	Variance
CP0	4	1	0.004	–	0.000	–	0.000	–
PM1	72	0	–	–	–	–	–	–
MNRP1	144	3	0.478	0.685	0.000	0.000	0.022	0.002
HWH1	204	3	0.355	0.361	0.001	0.000	0.000	0.000
RRP1	400	4	2.905	3.756	2.239	10.086	0.002	0.000
PM0	432	6	0.078	0.005	0.000	0.000	0.000	0.000
HWH0	1196	20	0.739	0.920	0.108	0.076	0.029	0.015
RRP0	1648	27	0.704	0.455	0.022	0.013	0.003	0.000
MNRP0	2420	39	0.652	0.330	0.033	0.017	0.004	0.000
∑:	6520	103						
	District-wide:		0.760		0.175		0.008	
	SE:		0.087		0.099		0.005	

+ - Division is ecozone, with roads subdivided into those without or with medians.
* - N is the total number of qtr-mi segments available in each zone.

Table 5.9: Optimal allocation of 100 qtr-mile segments among 9 subdivisions of District 4, to estimate abundance of each of three weed species (2005 data)

Division+	N* (possible)	No. segments to be examined next year		
		Canada thistle	Poison Ivy	Leafy spurge
CP0	4	2	2	2++
PM1	72	2	2	2
MNRP1	144	2	2	3
HWH1	204	3	2	2
RRP1	400	16	55	2
PM0	432	2	2	2
HWH0	1196	23	14	65
RRP0	1648	22	8	7
MNRP0	2420	28	13	15
Total:	6520	100	100	100

+ - Division is ecozone, with roads subdivided into those without or with medians.
* - N is the total number of qtr-mi segments available in each zone.
++ Value assigned using FUNCTION [=VLOOKUP(B2,LSAllocationTable,2)], B2 POINTS at the "N possible" value in same row

5.3.2 Challenges to application of optimum sample size and number

While the smaller sample sizes recommended above for high precision population estimation offer promise of both low sampling costs and high precision, there are inherent problems to be overcome. Most notable is the difficulty of navigating to the selected sites, whose location is referenced to highway mile marker position.

Locating the larger size sampling sites (e.g. 3 mile or 0.25 mile segments) in the field involves driving to the whole mile-marker point corresponding to the starting point of the segment; to get to the start of the 0.25 mile segment would further involve determining (using the odometer of your vehicle) the approximate number of yards (as odometer count is in $1/10^{th}$ –mile) to the starting point of the sampling site. Because most markings of these posts are in intervals of one mile (a few cases with $1/10^{th}$ mile), locating the starting point of a sampling site full mile long is easy and convenient. The same may be said for segment lengths which are significant fractions of a mile. On the other hand, navigating to a site 0.024 miles (264 ft) or 0.004 (21ft) miles long is difficult exercise.

This problem may be overcome by identifying the coordinates of each site to be used in the survey, feed the information to GPS units, and then use them to navigate to each site. Although this can be a faster approach, it assumes availability of GPS units with high spatial resolutions (such as the Trimble Pro-XR). This dictates success of the survey to availability of the appropriate equipment.

For the 2007 surveys, we have simplified the process of locating sites in the field by:

- Adopting segment size equivalent to 75-paces or 225ft (instead of original 1/20-mile or 264ft), and 5-pace or 14ft (instead of $1/250^{th}$-mile or 21ft). The latter will also enable operator maintain standard segment width using 7-ft survey stick.
- Selecting sampling sites from the population of $1/10^{th}$–mile mile marker positions. This way all sampling sites would be located in reference to a particular $1/10^{th}$-mile position, to which the operator can drive then ‘step’ to the (in multiples of 75-paces) to actual segment location.

5.4 Absence-Presence Survey

Discussions presented earlier in this chapter on optimum sample number and size, have highlighted the problems of using a small number of sampling sites in surveys for estimating populations in larger areas. All the problems mentioned are of concern to weed managers, but efficiency and economics of adopted sampling design are more critical. In an effort to provide possible solutions to the problem, it has been proposed that future sampling surveys at the Mn/DOT District 4 adopt shorter segments (14 ft) in conducting surveys, with only data on species presence or absence being recorded. Because less time is required to conduct such a survey, larger numbers of sampling sites can be visited compared to the mapping surveys requiring surveying larger size segments. This will not only save time spent on surveys, but would provide higher sampling accuracy due to larger number of sampling sites adopted.

5.4.1 Preparations for absence-presence surveys

Getting ready to conduct field surveys shall involve all the activities discussed in sections 5.0 to this point. For further details on procedures to these and other pertinent steps, the reader is referred to chapter 6 of this document.

5.4.2 Recommendations:

Based on our current analysis we are making the following recommendations for consideration by MnDOT District 4 management as they design weed future weed surveys.

- Mn/DOT should build a weed monitoring program around their worst weed problem, Canada thistle. Analysis of the 2004 and 2005 data showed that Canada thistle occurrence is well distributed across regions, hence sample selection based on this data would yield sample sites well distributed across ecological regions and road types.
- Sampling should involve stratification, by ecological regions, as well as by roadway type (i.e. whether highway is divided, hence has median, or undivided with no median). The two years' data showed a correlation between species occurrence, ecological region and presence/absence of median in roads.
- That Mn/DOT should use the smallest feasible sample unit (road segment length no greater than 1/20th mi) in its surveys. Analysis of previous years' data, segmented into 1/4th-mi. and 1/20th-mi., indicated that use of the shorter segments to be more efficient. Observed lower standard errors implied higher precision can be achieved with lower surveying cost.
- Mn/DOT should for now use budgeting to determine how many 1/20th-mi sampling sites they can afford to examine, at the same time be able to establish maximum standard error they can work with.
- The total number of sample units has been distributed among the 9 strata (combination of 5 ecological zones, and absence/presence of road median) using an optimal allocation based on the 2005 0.25-mile survey data. Future Mn/DOT survey efforts need follow procedures developed, as discussed in chapter 5 and 6
- The allocations in future years should be revised sequentially, i.e., 2006 results be used to plan 2007's effort, 2007 to 2008, and so forth.

In the future, MDOT should consider using sequential sampling rather than total numbers of segments. This will depend on what they actually need from the weed surveying program. In certain situations, Mn/DOT might be able to realize savings by ignoring certain species once their required precision (or treat-no treat decision) has been made in a given subdivision. The theory will need further exploring.

Chapter 6

Methods and procedures for selection of number and size of sample Unit

Sampling by Mn/DOT staff is designed to evaluate their current roadside noxious weed control program, and to budget for following years' operations/activities. Efficacy of the adopted survey design may be adduced from the achieved accuracy of estimating acres of right-of-way infested by the more abundant weed species. The procedures outlined below will be applied to the estimation of acres per-mile of roadway rights-of-way occupied by particular weed species. These procedures have been developed using District 4 as a pilot district, and can be adopted in other districts if modified to accommodate the different number and size of ecological zones and roadway miles in the districts.

6.1 Sampling units

The basic sample unit will be a 225 ft (or 75-pace) segment of roadway, including all non-paved parts of rights-of-way along both sides of pavement and median if present. In District 4, there are 16,332 locatable segments, identified by road number, milepost and 10ths of a mile in between. Road markers are divided into 10ths because they can be located easily from mileposts using a vehicle odometer. For example, reference point "MN200-66.2" would be on state highway 200, and begin 2/10ths of a mile from milepost 66 toward milepost 67. A master list of all possible segment reference points is compiled in the Excel spreadsheet "D4MasterMilePostList.xls."

6.2 Stratification of roadways

In a given year, a subset or sample of the listed segments needs to be examined, and this sample will be chosen as a stratified random sample chosen from points in nine roadway categories. The categories are defined by as a combination of ecozone and absence (-0) or presence (-1) of median: Chippewa Plains-0; Hardwood Hills-0, -1; Minnesota River Prairie-0, -1, Pine Moraines and Outwash Plains-0, -1; and Red River Prairie-0, -1. Here and in the associated data files, these categories are abbreviated as acronyms, for example, CP-0, HH-0, *etc*. Previous sampling in 2004 and 2005 indicated acres per mile of Canada thistle, poison ivy and leafy spurge varied substantially among categories, which indicates that stratifying by category will both assure coverage and improve district-level precision.

6.3 Determination of numbers of segments per road category

A sample will consist of a chosen number of segments (n = 100, or otherwise). That total will be distributed among the nine roadway categories using the spreadsheet, "WeedSamplingPlanner.xls." (Table 5.1 and 5.2) The spreadsheet enables one to assign sampling sites to the 9 categories proportional to number of roadway miles in the category. Once numbers per category are chosen, the actual set of segments to be examined will be chosen from the reference point list in “D4RoadMarkerList.xls” (Table 6.1) using functions and procedures available in Microsoft Excel. A new sample should be drawn each year, based the previous year’s sampling survey data. A sampling plan for the upcoming year should be based on the previous year’s sampling survey data. Once entered into the planner spreadsheet, managers can explore changes in total number of segments and their optimal distribution for the upcoming year.

6.3.1 Steps for finding out how many segments to examine in each of the nine road categories:

1. Open the spreadsheet “WeedSamplingPlanner.xls”, screen shot in Figures 5.1 and 5.2. This spreadsheet contains three worksheets, one for each of the three species surveyed in 2005. Each worksheet (a) summarizes past measurements, in acres per roadway mile, and calculates summary statistics by roadway category; (b) projects achievable precision for a new, revised district-wide total number of segments; and (c) calculates the optimal distribution for the new segments among the nine categories. The best distribution for one species is likely to be different from one for another species, because the optimal distribution is based in part acres per mile and variability, which differ among weed species. It is recommended that results for Canada thistle be used to define the district’s sampling plan, because that species is the driving problem.

2. Within the planner, use trial and error, substituting different values for “New total segments (75 paces each):” cell T8, and see resulting changes in “New ME/Mean (%):”, cell T13, and “Total time to survey new segments:”, cell Z11. Settle upon a new total, based on achievable precision, total sampling cost, or a compromise between the two.

3. The target number of segments (*n*s) for a new survey will be listed automatically, by road category, in the section “Optimal distribution,” cells S19-S27. Subject to the constraint that a minimum of two segments should be chosen from every category, the optimal distribution of the new total will produce the smallest, district-wide margin of error for the estimated mean acres per mile.

6.3.2 Steps for selecting the specific 75-pace segments to be examined:

1. Make a working copy of the file “MarkerListMaker.xls” (Table 6.1), open the new copy, and select the worksheet “MasterList.”

2. Freeze the values in all columns, labeled “Category” through “Rand().” The first three columns contain values linked in from D4RoadMarkerList.xls, and those in Rand() are produced by Excel’s RAND() function. All will be “hot” when the spreadsheet is opened. To freeze the current values, select all four columns (A-D), then “Edit…Copy,” then “Edit…Paste Special…Values” to paste current values over the selected columns. After pasting, new segment information and random numbers can only be obtained by opening a new copy of the original “RoadListMaker.xls.”

3. Reorganize the master list by sorting with Excel’s Sort procedure to find the segments to be used. These are the ones with the lowest random numbers. Select all columns in “MasterList,” and then use “Data…Sort” to execute a nested sort of segments within each of

the nine road categories. Under “Data…Sort”, click on Sort by <Road category> (ascending) and Then by <RAND()> (ascending). This will sort the segments within each category into ascending random order. Once completed, delete the entire “Rand()” column, which will no longer be needed.

4. Extract the labels for the chosen segments and place them into a second worksheet where they can be reorganized for field work. For each of the nine categories, select and Copy the desired number of segments (as determined with WeedSamplingPlanner), starting at the top of each category’s list, and then paste those rows into the “SelectedOnes” worksheet. These segments are the ones to be surveyed.

3. Resort the extracted list by SubDistrict and Hwy-Post.tenth, to organize them in a way that may be more convenient to drive to and map.

Table 6.1: A section of MasterMilePostList.xls of all 1/10th mile marker positions in all Mn/DOT managed highways in Mn/DOT’s District 4

SubDistrict	Category	Hwy-RefSpot	Rand()
Moorhead	CP-0	MN200-066.7	0.531154513
Moorhead	CP-0	MN200-066.6	0.131366825
Moorhead	CP-0	MN200-066.9	0.56504457
Moorhead	CP-0	MN200-066.5	0.629575066
Moorhead	CP-0	MN200-066.3	0.891649185
Moorhead	CP-0	MN200-066.1	0.176906205
Moorhead	CP-0	MN200-066.4	0.571308127
Moorhead	CP-0	MN200-066.8	0.700500158
Moorhead	CP-0	MN200-066.2	0.51997975
Moorhead	CP-0	MN200-066.0	0.881789959
Moorhead	HH-0	US59-252.2	0.873391915
Alex	HH-0	MN108-057.6	0.961389494
Fergus	HH-0	MN34-010.2	0.133192115
Fergus	HH-0	MN32-003.9	0.074960966
Alex	HH-0	MN29-098.8	0.104877655
Fergus	HH-0	MN108-029.7	0.092010557
Fergus	HH-0	US59-238.0	0.493614205
Moorhead	HH-0	MN87-000.9	0.178254138
Alex	HH-0	MN27-077.2	0.298102744
Alex	HH-0	MN114-019.9	0.610672741
Alex	HH-0	MN235-005.7	0.651763465
Alex	HH-0	MN29-072.4	0.606316012
Moorhead	HH-0	MN34-040.8	0.600532103
Moorhead	HH-0	MN34-045.6	0.777136031
Alex	HH-0	MN27-082.4	0.90691321
Fergus	HH-0	MN108-033.2	0.270803834

6.3.3 Steps for selecting the specific 7-pace segments to be examined:

Selection of required 7-pace segments can be conducted following the above 5 steps for selection of 75-pace segments. Substitute all references to 225ft (or 75-pace) with 14ft. Since surveying these segments is less labor intensive, a larger number of segments can be surveyed with minimal time and effort. It is recommended that a sample number of at least 200 be selected.

6.3.4 Processing Segments

To process each segment, begin by recording the examiner's name, time of arrival, and GPS coordinate of front of vehicle. Next, scout the segment quickly to determine if the entire right-of-way can be mapped. If accessible, walk with traffic 75 paces (225 ft) and place a road marker to designate the end of the segment; the front of the vehicle will mark its beginning. While returning to the vehicle, scout the same roadway edge to plan how to map it.

Map the segment by tracing (into GPS unit) the locations of weed patches or locations of isolated specimens. Do this for each noxious weed species. A patch is defined as a sprayable area occupied by a single species, two or more paces in longest dimension. Patches may be dense or sparse, but level of infestation will be disregarded. For the purpose of estimating chemical and applicator needs, sprayable area seems more meaningful than actual coverage area.

Map patches of each species. If patches of different species overlap, then trace around each one separately. If a given species is present, but specimens are isolated or in patches smaller than 2 paces long, then record the species as a dot on the map. When areas are collated, spots will be assigned an area of 3 square feet.

Complete this mapping procedure from pavement to edge of right-of-way, on both sides of the pavement, and in the median if present. When done, record time of departure.

If a chosen segment can not be mapped? A chosen segment may be inaccessible, because of flooding, construction or anything else. If so, then substitute a nearby replacement by continuing down the road and stopping at the next nearest accessible spot. On the SelectedOnes list, record the reason why the original one was unavailable, and record the GPS coordinates and "Hwy-Post.tenth" location of the substitute section that was actually examined.

6.3.5 Data produced.

After maps are processed, Mn/DOT should be able to extract the following:

a. Who surveyed a set of segments, and when they left "home" and began surveying
    i. For each segment,
    ii. Time/date of arrival
    iii. GPS coordinate and Segment Highway-milepost.tenth
    iv. Comment concerning accessibility, and if not, why not.
b. If mapped, then for each weed species,
    i. Species ID, total acres as sum (patch areas) plus spots, on both sides of roadway, and in median if present.

ii. Time/date of departure
iii. Time and date of return "home."

Surveyor IDs, arrival times and departure times will allow us to reconstruct the timeline of each surveyor's activities, and allow Mn/DOT to get reliable estimates of average traveling time between segments, and of average processing time per segment.

Measured areas of each of the different weed species from the current survey can then be entered into the D4WeedSamplingPlanner spreadsheet, to update the district's database, and revise a previously used plan for sampling in the next year.

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Appendix A. Annotated Bibliography

Reviews of publications relating to different facets of weed management are summarized in this appendix.

Introduction

Management of weeds occurring along roadsides is crucial for driver safety, pavement maintenance, and storm water management. This is usually a costly undertaking, demanding substantial financial, personnel and equipment allocations. Agencies charged with this responsibility contend with numerous challenges, many emerging following selection of type of control measures to be applied. Further, conflicts often arise due to different, diverse goals of the various agencies concerned with management of natural resources, as well as of the environment. For instance, differences arise between the need for maintenance of clean, clear-cut roadside environment, and conservation / preservation of certain vegetation species. Control measures approved for use under given situations may be in contravention of another agency's regulations. For example, herbicides allowed by the Federal Highway Administration (FHWA) may not meet approval of a forest service official for use in areas where noxious weed infestations may extend outside of road easements. Cost reduction considerations are often in opposition to environmental concerns, whose demands and goals are often contrary to those of the former. Interest in biodiversity preservation is contrary to the need to create the often preferred mono-species environment. Seed eradication through fumigation with Methyl bromide has also been faced with opposition in the banning use of this chemical due to environmental concerns.

This appendix is a presentation of publications covering various aspects of weed management and other related activities. Discussions are organized topic-wise to include:

- Weed Identification and Mapping
- Weed Inventory, Location and Distribution
- Weed Sampling Techniques
- Modeling and Prediction of Weed Location and Occurrence
- Land and Weed Management Practices
- Weed Control Measures
- Weed Management by DOTs in Select States

Weed Identification and Mapping

This section presents coverage on two general categories: methods commonly employed in identification of weed species along highways' right-of-ways, and techniques adopted in construction of weed maps. Abstracts/summaries on various journal and online publications covering techniques which are used in weed identification and mapping are presented. These range from traditional mapping techniques, such as scouting and ground surveying, to modern technologies, including analysis of maps digitized from low-altitude aerial photographs, to software tools used in generation of weed maps from scouting information, to remote sensing and GIS. This discussion forms a basis for comprehensive enumeration and documentation of techniques and methodologies internationally recognized as effective for weed identification and mapping. This also is a small step towards cross comparison and contrasting of the techniques.

Title: Montana Noxious Weed Survey and Mapping System
Authors: Cooksey, Diana ; Roger Sheley
Source: Montana State University
Weblink: http://www.montana.edu/wwwpb/pubs/mt9613.pdf

This publication, by the MSU Extension Service, provides information on the methods used to survey and map Montana's noxious weed populations. Weed survey data are integrated into GIS systems, including ArcView and CountyCAD. GPS systems are also utilized to track weed populations over time. The pamphlet includes information for those using basemaps to indicate locations of weed populations.

Title: Prescription maps for spatially variable herbicide application in no-till corn.
Authors: Brown, R.B.; Steckler, J.P.G.A.
Year: 1995
Source: Transactions of the ASAE. 38(6): 1659-1666.

Weed maps for fields of no-till corn (*Zea mays* L.) were prepared from image analysis of digitized low-altitude aerial photographs. These weed maps were imported into a Geographic Information System (GIS) and divided into independent subunits for spatially variable herbicide prescription. A decision model was designed for pre-plant and post-emergence weed control recommendations. Each subunit of the field weed map was submitted to this decision model to determine the optimum herbicide mix and application rate. The resulting prescription maps would be used to control a field sprayer and to apply the appropriate herbicide combination to each weedy area. Results indicate that herbicide use would have been reduced by more than 40% with this approach. This demonstrates a means to significantly reduce herbicide usage in crop production without sacrificing weed control or crop yield.

Title: Weed mapping using GPS, GIS and remote sensing.
Authors: McGowen, I.; Michelmore, M.
Year: 1997
Source: Improving weed management for the 21st century. Proceedings of the 9th biennial noxious weeds conference, Dubbo, Australia, 16-18 September 1997. Pg 33-42.

This paper discusses the use of global positioning systems (GPS), remote sensing and GIS [geographical information systems] for mapping weeds. Weed mapping is essential to determine whether weed infestations are increasing over time, are decreasing or are stable. While most conventional forms of weed mapping give reasonably accurate ideas of the location of weeds, accurate information on the actual area infested and the degree of infestation is difficult to obtain. It is concluded that in mapping weeds, the use of normal GPS allows reasonably accurate location of the position of the operator and the centre of a weed infestation. It is, however, not suitable for mapping the boundaries of an infestation due to programmed error fluctuations in the signal. An alternative is the use of differential GPS which corrects for this signal degradation. Remote sensing offers another means of objectively mapping and monitoring weeds, especially in inaccessible areas. The resolution of current satellites is such that it may be possible to measure dense and moderate infestations of certain weeds. Light to moderate infestations of pasture weeds, some woody weeds and some crop weeds can also be mapped using airborne sensors. The efficiency and use of weed mapping will be improved by incorporating the data into GIS. This allows the manipulation of the maps with other data to provide information on control strategies, potential weed spread and to compare infestation changes over time. The integration of remote sensing and GIS for weed mapping will improve the accuracy and usefulness of the data.

<u>Title</u>: Software for mapping and analyzing weed distributions: gWeedMap.
<u>Authors</u>: Krueger, D.W.; Coble, H.D.; Wilkerson, G.G.
<u>Year</u>: 1998
<u>Source</u>: Agronomy Journal. Vol. 90: 4, 552-556.

The spatial pattern of weeds in a field is often patchy. This pattern can be visualized with maps created by geographical information system (GIS) software, but this is often difficult to use and is expensive. A means of easily and economically generating weed maps was developed. This was accomplished by creating a PC-based Windows software tool to generate weed maps from scouting information. The scout enters weed data that has been collected in a gridded, systematic sampling protocol. From this information, the program creates a map for each weed species in the field. Scouting data can be density, percent cover, or any other type of measurement. Five data ranges are displayed on the map, with the user specifying the data values and map colors associated with each range. Various statistics are calculated, such as the average density of each species. Weed diversity in each field is determined with Shannon's diversity index and evenness index. These indices are also calculated with the density data weighted by the competitiveness of each weed species. This gives the weed ecologist a quantitative measure of the competitive diversity, which is related to the impact of the weed population on yield loss.

<u>Title</u>: Evaluating the accuracy of mapping weeds in seedling crops using airborne digital imaging: *Avena spp.* in seedling *triticale*
<u>Authors</u>: Lamb, D.W; Weedon, M.M; Rew, L.J.
<u>Year</u>: 1999
<u>Journal</u>: Weed Research. 39(6): 481-492

Airborne multispectral imaging has been used to map patches of *Avena spp*. (wild-oats) in a field of seedling *triticale* (X *Triticosecale*, *Wittmack*). Images of the target field were acquired using a four-camera airborne digital imaging system, recording in the infrared, red, green and blue wave-bands. Spectral information derived from images of 0.5-, 1.0-, 1.5- and 2.0-m spatial resolution were correlated with detailed on-ground weed density measurements to investigate the effect of image resolution on mapping accuracy. Comparisons between normalized-difference vegetation index (NDVI) or soil-adjusted vegetation index (SAVI) images and weed data achieved correlations of up to 71%. The highest correlation was achieved with the 0.5-m-resolution images and the lowest with the 2.0-m-resolution images. At 0.5-m resolution, NDVI images could not reliably discriminate weed populations of less than 28 weeds m2 from weed-free regions, while SAVI images could not discriminate populations of less than 17 weeds m2. At 1.0-, 1.5- and 2.0-m resolution, SAVI images could not discriminate populations of less than 23 weeds m2, while NDVI images again demonstrated a higher discrimination threshold. Results suggest that airborne multispectral imaging could be used as part of a stratified weed sampling system.

Title: Mapping the distribution of weeds in Great Britain in relation to national survey data and to soil type
Authors: Firbank, L.G.; Ellis, N.E.; Hill, M.O.; Lockwood, A. J.; Swetnam, R. D
Year: 1998
Source: Weed Research. Volume 38(1):1-10

A method is presented for using botanical survey and soil survey data to generate maps of the probability of occurrence of weeds in Britain across all habitats. For each species, data from a national, designed botanical survey were smoothed spatially, and the association between species distribution and soils was calculated using the botanical survey and 1 km square data on dominant and subdominant soils using national data. A logistic regression was fitted using the botanical survey data, and was interpolated across the whole country to generate the maps. The resulting maps show the probability of occurrence of species and species groups at the 2-km scale. They map the potential, rather than realized, risk of particular types of weed infestation, as they do not account for local management factors.

Title: Integrating remote sensing (aerial images), geographic information system (GIS), and global positioning system (GPS) data: the case of mapping weeds in a Moody County (South Dakota) field.
Authors: Thanapura, P.; Clay, S.A.; Clay, D.E.; Cole, C.; Dalsted, K; O'Neill, M.; Robert, P.C. (ed.); Rust, R.H. (ed.); Larson, W.E.
Year: 2001
Source: Proceedings of the 5th International Conference on Precision Agriculture, Bloomington, Minnesota, USA, 16-19 July, 2000. pg 1-10 American Society of Agronomy; Madison; USA

Ground-based weed sampling is labour intensive and expensive. However, research indicates that by understanding weed variability, management decisions and profitability can be improved. Remote sensing is a technique that provides an overview of the field. The objective of this study, conducted in Moody County, South Dakota, USA, was to develop a methodology for creating post-emergent herbicide application maps for a 65-ha field using remote sensing. Single-band level-slicing was done on a near-infrared (NIR) band collected by aerial platform on 14 June 1999 and was compared to information collected by ground-truthing over 1100 points on the same date. Areas with weeds had lower brightness values (BV) than areas without weeds. Brightness value boundaries for "treat" and "no-treat" zones were set up either by using data that contained 85% of the values from the weedy areas (80-100 BV) or using the 95% confidence interval (97-99) of the mean BV for the weedy areas. Using the BV range from 80 to 110 resulted in maps with contiguous treatment areas, and a producer accuracy of 85%. Using this criterion, about 42% of the field would not be treated and the user accuracy for "no-treat" zones was 90%. The 95% confidence interval method reduced the "treat" zone to 26% of the field, however, 84% of the areas that should have been treated were placed in the "no-treat" zone, clearly much too great an error for a producer. These data indicate that remote sensed imagery can be an important tool to locate treatment areas, but care must be taken in choosing the appropriate criteria on which to base recommendations.

Title: Purple Loosestrife: a coordinated education, mapping and control effort
Author: Pirosko, Carri B.
Date: June 2002
Source: Proceedings of the California Weed Science Society; Vol. 54. Pg 87-89

In 1999, the Integrated Pest Control branch of the California Department of Food and Agriculture (CDFA) began conducting a program to prevent the spread of purple loosestrife (*Lythrum salicaria*), as well as the detection of new *L. salicaria* populations, and the treatment of affected areas. This project consisted of five parts: 1).The education and training of California Native Plant Society members, garden clubs, and the general public about purple loosestrife, it's origins, and treatment measures. 2). The survey and mapping of all purple loosestrife sites using GPS and GIS technologies. 3). Organization of meetings of regional cooperators for the development of site-specific adaptive management plans, which are based on weed distribution data from the first season of the project. 4). Comprehensive local control and eradication efforts; this includes mechanical removal, spot treatment with glyphosphate herbicide ("Rodeo®" brand), and the controlled release of biological control agents (including root and seed/flower-eating weevils, and two varieties of leaf-eating beetles). 5). Assessment of the project's success as a function of regional adaptive management plans. The author stressed the importance of prevention and early eradication to increase environmental and economic viability.

Title: Development and Testing of a Vegetation and Land Cover Map of Maine
Authors: Hepinstall, Jeffrey A.; Sader, Steven A.; Krohn, William B.; Boone, Randall B.; Bartlett, Roscoe I.
Date: September 1999
Source: Maine Agricultural and Forest Experiment Station (University of Maine): Technical Bulletin 173

This project was designed to utilize satellite imagery data, aerial videography, and various ancillary data to create a vegetation and land cover map of the state of Maine. The information was to be specifically used for the Maine Gap Project, in conjunction with the USGS' Biological Resources Division to create a large-scale assessment of biodiversity in the US. Satellite data was acquired from a variety of sensors. These included the Landsat Thematic Mapper (TM), used exclusively for land cover classification. Additional data came from the Multi-Resolution Land Characteristics (MRLC) program, which maintains an image archive. Flights were conducted in June and October 1994 for aerial video recording. Flight patterns were conducted to progress with plant phenology.

Title: Potential of airborne hyperspectral remote sensing to detect nitrogen deficiency and weed infestation in corn
Authors: Goel, P.K.; Prasher, S.O.; Landry, J.A.; Patel, R.M.; Bonnell, R.B.; Viau, A.A. and J.R. Miller
Date: February 2003
Source: Computers and Electronics in Agriculture; 38(2): 99-124

A compact airborne spectrographic imager (CASI) was used to obtain images over a field that had been set up to study the effects of various nitrogen application rates and weed control on corn (*Zea mays*). The objective was to determine to what extent the reflectance obtained in the 72 visible and near-infrared (NIR) wavebands (from 409 to 947 nm) might be related to differences associated with combinations of weed control (none, full, grasses only or broad leafs only) and nitrogen application rate (60, 120 or 250 kg/ha). Plots were arranged in split-plot experiment in completely randomized design at the McGill University Research Farm on Macdonald Campus, Ste Anne de Bellevue, Que., Canada. Weeding treatments were assigned to the main-plot units, and nitrogen rates to the sub-plot units. Three flights were made during the growing season. Data were analyzed for each flight and each band separately, then regrouped into series of neighboring bands yielding identical analyses with respect to the significance of the main effects and interactions on reflectance. The results indicate that the reflectance of corn is significantly influenced ($\alpha=0.05$) at certain wavelengths by the presence of weeds, the nitrogen rates and their interaction. The influence of weeds was most easily observed in the data from the second flight (August 5, 2000), about 9 weeks after planting. The nitrogen effect was detectable in all the three flights. Differences in response due to nitrogen stress were most evident at 498 nm and in the band at 671 nm. In these bands, differences due to nitrogen levels were observed at all growth stages, and the presence of weeds had no interactive effect. Differences in other regions, whether related to nitrogen, weeds or the combination of the two, appeared to be dependent on the growth stage. Furthermore, results comparable to those of the hyperspectral sensor were obtained when a multispectral sensor was simulated, indicating little advantage of using the former.

Title: Montana Noxious Weed Survey and Mapping System
Authors: Burch, Dave; Larson, Jim
Source: Montana Noxious Weed Survey and Mapping System (MT Dept of Agriculture)
Weblink: http://www.montana.edu/places/mtweeds/

This website contains information on the distribution of weed populations throughout Montana, as a part of the Montana Natural Resource Information System (NRIS) Thematic Mapper. The site includes links to publications and downloads about weed infestations, information about the system's database, descriptions of works in progress, and additional links providing information about the Thematic Mapper. As described by the project's creators, the objectives of the mapping included the development and maintenance of "a statewide spatial database for noxious weed management". Additionally, the project aims to calculate the total area affected by weeds, the rate of spread, and the evaluation of the effectiveness of GIS/GPS systems in weed mapping. Objectives and methods can be found under the "Slideshow" link.

Title: Weed Mapping in the Blackfoot River Basin
Source: Geodata Services, Inc. (MT)
Weblink: http://www.geodata-mt.com/Weeds/weeds02a.htm

Geodata Services, a GIS mapping company and software distributor, provides GIS services to various organizations, including the Rocky Mountain Elk Foundation and the USFWS. In this case, Geodata created basemaps of spatial weed distributions within the Blackfoot River Basin. The main site provides links to project data, as well as an overview of how the maps were created in GIS.

Title: California Weed Mapping Handbook
Source: California Department of Agriculture
Date: September 2002
Weblink: http://cain.nbii.gov/weedhandbook/CalifWeedMappingHandbook.pdf

This online handbook provides step-by-step instructions on how to create a weed mapping database using GIS and GPS systems. Chapters include basic mapping information, shared data standards, GPS data collection, map data management, and a list of resource appendices.

Weed Inventory, Location and Distribution

Weed inventory and distribution information is crucial for correct diagnoses and decisions and selection of appropriate control measures. References cited in this section represent some of the available literature on techniques for establishing location and distribution of infestations by various weeds along highways right-of-ways, as well as in surrounding areas. Applications of technologies, such as sites specific weed management, rely on this information.

Title: Measures that describe weed spatial patterns at different levels of resolution and their applications for patch spraying of weeds
Authors: Wallinga, J.; Groeneveld, R.M.W.; Lotz, L.A.P
Year: 1998
Source: Weed Research; Volume 38(5): 351-360

If weeds occur in aggregated spatial patterns, it is possible to reduce herbicide use by spraying only weed patches. The reduction in herbicide use will then depend on the spatial resolution of the patch sprayer and the weed-free area at that level of resolution. Three distance measures are presented that describe the weed spatial pattern at different levels of resolution. They give information on aspects of pattern that are relevant to patch spraying. The distance measures were applied to a spatial pattern of *Galium aparine L*. seedlings recorded in an area of 18.0 m - 32.4 m. In this area, the herbicide use of an idealized patch sprayer that detects and sprays all weeds with a spatial resolution of 1.0 m would be 41% of the amount required for a whole-field application. Spraying with a finer spatial resolution of 0.5 m would give a further 26% reduction in herbicide use.

Title: Does temperature limit the invasion of *Impatiens glandulifera* and *Heracleum mantegazzianum* in the UK?
Authors: S. G. Willis and P. E. Hulme.
Year: 2002
Source: Functional Ecology 16: 4, 530-539.

1. *Impatiens glandulifera Royle* and *Heracleum mantegazzianum Sommier et Levier* are widespread, non-indigenous plant species in the UK. A variety of correlational analyses suggest that their spatial extent is limited by climate, although no experimental studies have tested this hypothesis. This paper reports the first detailed experimental examination of the impact of climate on the performance of the two species. 2. Seeds of each species were sown, in each of 2 years, in replicated plots along an elevational gradient (10-600 m a.s.l.) in north-east England. Both species germinated readily at all elevations, even in areas well above their current limits within the study area. The plants were, however, smaller at higher altitudes. *Impatiens glandulifera* also produced fewer seeds with increasing elevation. 3. Plant performance was assessed in relation to actual and interpolated climate data along the elevational transect. For *H. mantegazzianum*, the timing of germination was correlated most strongly with the pre-emergence heat sum; for *I. glandulifera* this relationship was significant in one year only. Maximum height of both species was correlated with increasing post-emergence heat sum, as was pod production by *I. glandulifera*. The biomass of second-year *H. mantegazzianum* plants varied nonlinearly with post-emergence heat sum. For both species, overwinter survival of seeds was not related to winter temperature or frost days. Overwinter survival of first-year H. *mantegazzianum* plants declined with increasing frost incidence. 4. The results suggest that, of the two species, only I. *glandulifera* is currently most limited by temperature, although this is not the only factor determining the distribution of the species.

Title: North America Invasive Plant Mapping Standards (NAWMA)
Author: North American Weed Management Association, endorsed by Federal Interagency Committee for the Management of Noxious and Exotic Weeds
Date: May 7, 2002
Source: CD-ROM

This publication discusses methods of sampling and inventorying weed infestation as a valuable tool for practical and economical weed management strategies. The efforts to control invasive plants have often been described as a war on weeds. By many estimates, we are losing this war. In order to be more effective, many weed managers are adopting a more strategic approach. One of the most overlooked, and often most critical determinant of who wins a war is the intelligence gathered prior to any action occurring on the field. The same holds true for improving the efficiency and success of invasive weed management. Invasive species inventories will not kill weeds, but are an invaluable planning tool to help get the most out of limited weed management dollars. Inventories can also be useful in the planning phases of management efforts, maps and inventory information are critical to monitoring efforts. No matter what tool is used to manage weeds, monitoring should be done to evaluate the effectiveness and make sure the area has not been re-infested.

Weed Sampling Techniques

Sampling is an important tool for development of estimates of weed population data for large areas where it is otherwise difficult to survey in full. In practice, population estimates obtained from a limited number of select, representative (sample) sections is adopted for extrapolation of fairly accurate infestation maps over large, otherwise inaccessible areas. Questions often arise as to the adequacy of such samples to offer true and accurate representations of the real ground situation in the entire area. Articles summarized in this section present discussions on sampling techniques for determination of the spatial distribution of weeds, and also highlight some of the limitations that current sampling and analytical methodologies suffer. Suggestions on how some of the inadequacies may be addressed are presented. Some references are an attempt to provide validity to the application of sampling methods for development of weed distribution estimates in given localities. The types of statistical distributions used to characterize the populations of noxious weeds are also discussed.

Title: Spatial distribution of weeds in arable crops: are current sampling and analytical methods appropriate?
Authors: Rew, L.J.; Cousens, R.D.
Year: 2001
Source: Weed Research, February 2001, vol. 41, no. 1, pp. 1-18

This paper reviews the literature concerning the spatial distribution of weeds; highlighting the limitations of our current sampling and analytical methodologies, and suggesting how these inadequacies can be addressed. Most research studies have used discrete sampling, i.e. weeds are counted within a quadrat, on a grid basis. Few have mapped weeds at a whole-field scale, either with a resolution appropriate to spraying operations or key ecological processes. Statistical analyses used to describe the data can be divided into two main types, spatially implicit (also at the scale of the sampling unit) or spatially explicit, in which the location of individuals is included in the analyses. Spatially implicit methods can be strongly affected by quadrat size and mean density and are of doubtful benefit. More attention is required to address sampling resolution issues for spatially explicit methods. Our understanding of the formation and dynamics of spatial pattern, as well as predicting the consequences of site-specific management, can be improved with models. Unfortunately, most models consider only newly expanding patches and appear incapable of predicting spatial distributions when an area has been fully invaded. More detailed biological information is required if models are to become more realistic and informative. We also need to ensure that we understand the spatial processes in the context of the whole field environment, to optimize the success of site-specific weed management in the longer term.

Title: Spatial weed distribution: Can it be used to improve weed management
Author: Hartzler, Bob
Source: Iowa State University
Weblink: http://www.weeds.iastate.edu/mgmt/qtr99-1/spatial.htm

This article examines three identified types of distributions used to characterize populations of noxious weeds in an agricultural setting. These include; Regular (widespread), Random, and Patchy. Causes of the most common type of distribution, Patchy, are related to various soil characteristics (i.e. pH, salinity, limestone content, K+ levels).

Title: Determination of weed distribution patterns over field via mapping.
Authors: Onen, H; Ozer, Z.
Year: 2001
Source: Turkiye-Herboloji-Dergisi. Vol. 4: 2, pp. 74-83

This study was conducted to determine the weed distribution patterns in a field and their implications for weed control. A wheat field in Turkey was divided into 351 grids of 5 m x 5 m. A 0.25 m2 area was surveyed in each grid for the number of total or specific weeds using quadrats. Distribution maps for weeds in general and for specific weeds were prepared using ArcView GIS Version 3.1 software. Weed density counted in 5 m x 5 m grids was between 0 and 588 plants/m2 (average 135.1 plants/m2). Minimum, maximum and average densities of significant weeds were as follows: *Bifora radians* 0, 528, 46.02; *Sinapis arvensis* 0, 372, 27; *Polygonum aviculare* 0, 204, 15.9; *Chenopodium album* 0, 256, 11,5; *Polygonum convolvulus* [*Fallopia convolvulus*] 0, 232, 6.63; *Lactuca serriola* 0, 188, 6.48; *Galium aparine* 0, 68, 3.51, and *Equisetum arvense* 0, 56 and 2.01. In conclusion, we found that weed distribution patterns showed significant changes over the field and aggregations were detected in places. We speculate that herbicide application levels could be reduced by using weed maps.

Modeling and Prediction of Weed Location and Occurrence

Weed detection and delineation of infestations are often carried out by using ground survey techniques. However, such methods can be inefficient and expensive in detecting sparse infestations. The distribution of known weed species over a large region may be affected by various landscape variables such as elevation, slope, and aspect. These exogenous variables may be used to develop prediction models to estimate the potential for invasion of the weed in question into new areas. Simulation and modeling techniques have proven applicable for determining weed location and distribution. These tools can be applied in the derivation of a statistically justifiable probability response surface for a target species. Such data is invaluable to managers and decision makers regarding weed management especially in areas with limited field data. Papers in this section offer discussions on various methods adopted for predicting location and patchy distribution of weeds in fields.

Title: A PCA-based modelling technique for predicting environmental suitability for organisms from presence records
Authors: Robertson, M. P.; Caithness, N.; Villet, M.H.
Year: 2001
Journal: Diversity & Distributions, Vol.7 (1-2): 15-27

We present a correlative modelling technique that uses locality records (associated with species presence) and a set of predictor variables to produce a statistically justifiable probability response surface for a target species. The probability response surface indicates the suitability of each grid cell in a map for the target species in terms of the suite of predictor variables. The technique constructs a hyperspace for the target species using principal component axes derived from a principal components analysis performed on a training dataset. The training dataset comprises the values of the predictor variables associated with the localities where the species has been recorded as present. The origin of this hyperspace is taken to characterize the centre of the niche of the organism. All the localities (grid-cells) in the map region are then fitted into this hyperspace using the values of the predictor variables at these localities (the prediction dataset). The Euclidean distance from any locality to the origin of the hyperspace gives a measure of the 'centrality' of that locality in the hyperspace. These distances are used to derive probability values for each grid cell in the map region. The modelling technique was applied to bioclimatic data to predict bioclimatic suitability for three alien invasive plant species (*Lantana camara* L., *Ricinus communis* L. and *Solanum mauritianum Scop*.) in South Africa, Lesotho and Swaziland. The models were tested against independent test records by calculating area under the curve (AUC) values of receiver operator characteristic (ROC) curves and kappa statistics. There was good agreement between the models and the independent test records. The pre-processing of climatic variable data to reduce the deleterious effects of multicollinearity, and the use of stopping rules to prevent over-fitting of the models are important aspects of the modelling process.

Title: Predicting the likelihood of yellow starthistle (*Centaurea solstitialis*) occurrence using landscape characteristics
Authors: Shafii, Bahman; Price, William J.; Prather, Timothy S.; Lass, Lawrence W. and Donald C. Thill
Year: 2003
Source: Weed Science. Vol. 51, No. 5, pp. 748–751.

Yellow starthistle is an invasive plant species common in the semiarid climate of central Idaho and other western states. Early detection of yellow starthistle and estimation of its infestation potential in semiarid grasslands have important scientific and managerial implications. Weed detection and delineation of infestations are often carried out by using ground survey techniques. However, such methods can be inefficient and expensive in detecting sparse infestations. The distribution of yellow starthistle over a large region may be affected by various landscape variables such as elevation, slope, and aspect. These exogenous variables may be used to develop prediction models to estimate the potential for yellow starthistle invasion into new areas. A nonlinear prediction model has been developed using a polar coordinate transformation of landscape characteristics to predict the likelihood of yellow starthistle occurrence in north-central Idaho. The study region included the lower Snake River and parts of the Salmon and Clearwater basins encompassing various land-use (range, pasture, and forest) categories. The model provided accurate estimates of yellow starthistle incidence within each specified land-use category and performed well in subsequent statistical validations. This prediction model can assist land managers in focusing their efforts by identifying specific areas for survey.

Title: The use of thermal time to model common lambsquarters (*Chenopodium albumn*) seedling emergence in corn
Authors: Leblanc, Maryse L.; Cloutier, Daniel C.; Stewart, Katrine A. and Chantal Hamel
Year: 2003
Source: Weed Science. Vol. 51, No. 5, pp. 718-724

A mathematical model was developed to predict common lambsquarters seedling emergence in southwestern Quebec. The model was based on the thermal-time concept, using air temperatures in the double-sine calculation method. The model was built using data from five experiment-years for corn naturally infested with weed populations. Once developed, the model was calibrated using different crop seedbed preparation times. The base temperature was then adjusted for each time of seedbed preparation. A power regression function was used to relate adjusted base temperatures and the accumulated thermal units at seedbed preparation time. A modified Weibull function was then fitted to the field emergence data, expressed as the cumulative proportion of the total seedling emergence over the growing season as a function of cumulative thermal units. The simplicity and accuracy of this model would make it an excellent tool to predict common lambsquarters seedling emergence in field situations, facilitating the determination of the timing of scouting in integrated weed management systems.

Title: Does kriging predict weed distributions accurately enough for site-specific weed control?
Authors: Rew, L. J.; Whelan, B. and A. B. Mcbratney
Year: 2001
Journal: Weed Research. Vol. 41 No. 3 pp. 245

Numerous studies have demonstrated the patchy distribution of weeds within fields. The majority of these studies have used discrete sampling, recording weed densities at the intersections of regular grids. In this study, Avena spp. seedlings were recorded on square grids at four sites. The data were then divided into test and real data sets using the whole, two-thirds and one-half of the data to evaluate the consistency of global variogram models and accuracy of ordinary kriging estimates. Kriging provided poor weed density estimates at both very low and high densities, i.e. data were smoothed when compared with true values. Grid sampling took considerable time and, therefore, money to complete, whereas continuous sampling with multispectral imagery (performed at one site) was much quicker and at a finer resolution. It is suggested that sampling systems that collect continuous rather than discrete data are currently more appropriate for site-specific weed management.

Title: Predicting the spatial distribution of non-indigenous riparian weeds: issues of spatial scale and extent
Authors: Collingham, Yvonne C.; Wadsworth, Richard A.; Huntley, Brian and Philip E. Hulme
Year: 2000
Journal: Journal of Applied Ecology. (Suppl.1) Vol. 37 Issue 1 pp. 13-27

The existence of a hierarchical scheme of environmental controls on the spatial distribution of plant species was explored for three non-indigenous weeds, *Fallopia japonica*, *Heracleum mantegazzianum* and *Impatiens glandulifera*, in the British Isles. Logistic regression analyses of the presence/absence of the three weed species examined the relative importance of 60 environmental variables, encompassing land cover, geology and climate. Analyses were undertaken using variables assessed at a hectad (10 x 10 km) or tetrad (2 x 2 km) resolution at national (England and Wales) and regional (County Durham, UK) spatial extents. The ranges of all three species in the British Isles are currently increasing, and the non-equilibrium nature of their distribution limited the goodness-of-fit of logistic models. Interpretation of whether a species has expanded to occupy entirely its potential spatial range was scale-dependent, and species' distributions, when viewed at coarser spatial scales, may be more likely to be interpreted as having reached stasis. Spatial autocorrelation was more evident at the finer tetrad spatial resolution for both *F. japonica* and *I. glandulifera*, but not evident at all for *H. mantegazzianum*. Only the distribution of *I. glandulifera* revealed significant spatial autocorrelation among hectads at the national scale. These patterns appear related to the different dispersal mechanisms of the three species. The majority of the environmental variables identified as important at the tetrad resolution for County Durham were also important at the hectad resolution for England and Wales for both *F. japonica* and *I. glandulifera*, but not for *H. mantegazzianum*. However, for all three species the environmental variables identified as significant were consistent with qualitative descriptions of the species' habitat characteristics. There was no evidence of a hierarchy of environmental controls. At the regional extent, scaling-up species' distributions from tetrads to hectads was relatively successful, but scaling-down was not. The coarser resolution models were too unrefined to model fine-scale distributions successfully. Similarly, at a coarse hectad resolution, regional models were poor predictors of national species' distributions. It therefore appears that scaling-up from fine to coarse resolution is appropriate when spatial extent is held constant, and focusing-down from large to small spatial extents is appropriate when data resolution is held constant.

Title: Are weed population dynamics chaotic?
Authors: Freckleton, Robert P. and Andrew R. Watkinson
Year: 2002
Source: Journal of Applied Ecology 39: 5, pp. 699-707.

There have been suggestions that the population dynamics of weeds may show chaotic dynamics, and that therefore it will not be possible to predict the impact of changing management regimes on weed abundance. The instability of weed populations is presumed to result either from overcompensating yield-density responses or from threshold management. 2. Using theoretical arguments and empirical evidence we argue that this contention is likely to be incorrect. 3. Overcompensating yield-density responses are unlikely in plant populations and this point has been extensively discussed. Such responses have only been observed in high-density artificially sown stands of weed populations. The form of chaos that results from threshold management is a consequence of high population growth resulting from the cessation of management when weed densities are lower than a threshold level. Consequently the dynamics of such populations may be argued to be extrinsically rather than intrinsically driven. 4. There are many studies that have shown weed populations to be dynamically stable, both spatially and temporally. Here we present an analysis of data from the Broadbalk experiment that demonstrates long-term stability of 12 species of common weeds over a 12-year period. Using parameter estimates derived from the literature we show that the stability of these populations is similar to other annual species, both weedy and non-weedy. 5. We argue that weed population dynamics are more generally better viewed as resulting from the impacts of broad-scale types of management, as well as temporal variability in population numbers. The significance of chaotic dynamics is likely to be minimal

Title: Simulating the spread and management of alien riparian weeds: are they out of control?.
Authors: Wadsworth, R.A.; Collingham, Y.C.; Willis, S.G.; Huntley, B. and P.E. Hulme
Year: 2000
Journal: Journal of Applied Ecology 37: 1, pp.28-38.

This paper examines the circumstances under which control programmes may reduce the range of two widespread invasive weeds of riparian habitats: *Impatiens glandulifera* (Himalayan balsam) and *Heracleum mantegazzianum* (giant hogweed). The spread of both species was modelled using MIGRATE, a spatially explicit model that incorporates realistic demographic parameters and multiple dispersal mechanisms. Simulations of a range of control scenarios were run within a geographical information system (GIS) using authentic landscapes based on topographic, hydrological and land cover maps of County Durham, UK. Results were interpreted at both a catchment and a regional scale. Six representative strategies were explored that prioritized control as follows: at random, in relation to human population density, or by the size, age (new and old) or spatial distribution of weed populations. These strategies were assessed at different intensities of management (area treated per year) and for varying deficiencies (proportion of plants destroyed) as well as the timeliness (how long since the species became established) of implementations. Strategies that prioritized control based on weed population and spatial characteristics were most effective, with plant population size and spatial distribution being the key parameters. The reduction in geographical range within a catchment or region following control was always greater for H. *mantegazzianum* than I. *glandulifera* due to its slower rate of spread. Successful control of both species at a regional scale is only possible for strategies based on species distribution data, undertaken at relatively high intensities and deficiencies. The importance of understanding the spatial structure of the population and potential habitat available, as well as being able to monitor the progress of the eradication program, is highlighted. Tentative conclusions are offered as to the feasibility of eradicating these species at a regional scale.

Title: Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful?
Authors: Pearson, Richard G. and Terence P. Dawson
Year: 2003
Source: Global Ecology and Biogeography 12: 5, pp. 361-371.

Modelling strategies for predicting the potential impacts of climate change on the natural distribution of species have often focused on the characterization of a species' bioclimate envelope.

A number of recent critiques have questioned the validity of this approach by pointing to the many factors other than climate that play an important part in determining species distributions and the dynamics of distribution changes. Such factors include biotic interactions, evolutionary change and dispersal ability. This paper reviews and evaluates criticisms of bioclimate envelope models and discusses the implications of these criticisms for the different modelling strategies employed. It is proposed that, although the complexity of the natural system presents fundamental limits to predictive modelling, the bioclimate envelope approach can provide a useful first approximation as to the potentially dramatic impact of climate change on biodiversity. However, it is stressed that the spatial scale at which these models are applied is of fundamental importance, and that model results should not be interpreted without due consideration of the limitations involved. A hierarchical modelling framework is proposed through which some of these limitations can be addressed within a broader, scale-dependent context.

Title: Evaluating presence-absence models in ecology: the need to account for prevalence.
Authors: Manel, Stéphanie; Williams, H. Ceri and S.J. Ormerod.
Year: 2001
Source: Journal of Applied Ecology 38: 5, pp. 921-931.

Models for predicting the distribution of organisms from environmental data are widespread in ecology and conservation biology. Their performance is invariably evaluated from the percentage success at predicting occurrence at test locations. Using logistic regression with real data from 34 families of aquatic invertebrates in 180 Himalayan streams, we illustrate how this widespread measure of predictive accuracy is affected systematically by the prevalence (i.e. the frequency of occurrence) of the target organism. Many evaluations of presence–absence models by ecologists are inherently misleading. With the same invertebrate models, we examined alternative performance measures used in remote sensing and medical diagnostics. We particularly explored receiver-operating characteristic (ROC) plots, from which were derived (i) the area under each curve (AUC), considered an effective indicator of model performance independent of the threshold probability at which the presence of the target organism is accepted, and (ii) optimized probability thresholds that maximize the percentage of true absences and presences that are correctly identified. We also evaluated Cohen's kappa, a measure of the proportion of all possible cases of presence or absence that are predicted correctly after accounting for chance effects. AUC measures from ROC plots were independent of prevalence, but highly significantly correlated with the much more easily computed kappa. Moreover, when applied in predictive mode to test data, models with thresholds optimized by ROC erroneously overestimated true occurrence among scarcer organisms, often those of greatest conservation interest. We advocate caution in using ROC methods to optimize thresholds required for real prediction. Our strongest recommendation is that ecologists reduce their reliance on prediction success as a performance measure in presence–absence modelling. Cohen's kappa provides a simple, effective, standardized and appropriate statistic for evaluating or comparing presence–absence models, even those based on different statistical algorithms. None of the performance measures we examined tests the statistical significance of predictive accuracy, and we identify this as a priority area for research and development.

Title: Prediction of weed density: the increase of error with prediction interval, and the use of long-term prediction for weed management
Authors: Wallinga, J.; Grasman, J.; Groeneveld, R. M. W.; Kropff, M.J.; and L.A.P. Lotz
Date: April 1999
Source: Journal of Applied Ecology. Vol. 36, issue 2. pp. 307-317

This paper describes a study of the population dynamics of *Stellaria media* in crop rotation. From the study, a model of weed population dynamics was constructed. The authors note that there has been little research into the accuracy of long-term prediction models. It was found that when the prediction interval was enlarged, any errors in initial density measurement resulted in a prediction error that was independent of the prediction interval. Errors in growth rate measurement had a greater impact on prediction effectiveness. The study concludes that “the growth of error is positively related to the frequency of years in which the weeds are left uncontrolled” (Pg. 314). Researchers also addressed some practical aspects of weed control, such as economic return. Associated economic calculations indicated that weeds should not be treated if they occur below a particular density threshold, and should be treated if they occurred above the density threshold.

Title: Incorporation of weed spatial variability into the weed control decision-making process
Authors: Zanin, G.; Berti, A.; and L. Riello
Year: 1998
Journal: Weed Research. Vol. 38: (2), pp.107 - 118

Floral surveys were carried out on a field of 28 m 100 m on the nodes of a regular 2 m 2 m grid, using a rectangular sampling area of 25 cm 30 cm. In total, 765 units were sampled, each one characterized by the spatial co-ordinates and the number of seedlings of different weed species. The spatial representation of the weeds was obtained with kriging. Simulations were carried out for *Amaranthus* spp., which had the highest frequency and density (221 plants m2), and *Portulaca oleracea* L., a species that combined a more aggregated distribution with a medium-high density (27 plants m2). The results obtained clearly indicated that the usefulness of geostatistical procedures depends on the type of question posed by the user. If the goal is to estimate weed density and, consequently, crop yield loss, kriging appears to overburden the decision-making process, without improving the estimates obtained. This procedure becomes useful for obtaining weed infestation maps to be used for intermittent spraying applications. The reliability of these maps increases with the number of samples used for kriging. With the more aggregated species, at least 50 samples are required to obtain an infestation map. The reduction in the area to be treated depends on the threshold level adopted and on the number of samples used for kriging. With a threshold around the break-even point for most post-emergence treatments, this reduction varies from 10% to 40% with maps obtained from 50 and 175 samples respectively. The usefulness of infestation maps obtained with kriging for improving the decision-making process is strictly dependent on the weed patch dynamics: if these patches remain relatively stable over time, kriging can be carried out periodically without overburdening the decision-making process, whereas, if they are not stable, maps need to be drawn up each year, with a significant increase in costs.

Land and Weed Management Practices

Availability of accurate weed information is critical for selection and implementation of appropriate weed management methods. In practice, there exist diverse techniques which may be adopted in acquisition of this information. However, there also are limitations associated with adoption of any of these methods. Articles in this section discuss findings from studies on techniques used to determine weed presence and distribution in an area, and on application of weed vegetation analysis to the study of weed population shift, among others. Publications on management of agricultural inputs (precision agriculture) for profitable farming and effective weed management are discussed. A discussion of the application of remote sensing, GIS and GPS technologies in land and weed management is presented.

Title: Team Leafy Spurge Links Technology and People to Manage Weed
Author: Stelljes, Kathryn Barry
Date: November 2001
Source: Agricultural Research Vol. 48, issue 3. pp. 15

This brief article deals with the Agriculture Research Service's TEAM—The Ecological Area-wide Management of Leafy Spurge. The initiative, started in 1997, aims to increase public awareness of the Leafy Spurge epidemic, and to aid ranchers and land managers in the control of the weed. TEAM established a demonstration site along 300 miles of the Little Missouri drainage basin, which covers a variety of habitats. Scientists demonstrated the effectiveness of different combinations of biological controls, grazing, and herbicide applications during nine events. TEAM distributed more than 47 million *Aphthona* beetles to ranchers and land managers during the 4 years it was active.

Title: Noxious and Nuisance Plant Management Information System (PMIS – version 5.3)
Author: US Army Corps of Engineers, Engineering Research and Development Center
Year: 2000
Source: Department of the Army, Engineer and Research Development Center, Corps of Engineer, Waterways experiment station, CEERD-EE-A (CD-ROM)

This management information system offers an invaluable tool for identification of weed species, details information on weed control strategies (chemical, biological, mechanical, cultural and integrated). This information system offers an interactive species identification component and assignment of appropriate control measure.

Title: Hyperspectral imaging: a potential tool for improving weed and herbicide management.
Authors: Bechdol, M.A.; Gualtieri, J.A ; Hunt, J.T.; Chettri, S.; Garegnani, J.; Robert, P.C. (ed.); Rust, R.H. (ed.); Larson, W.E.
Year: 2001
Source: Proceedings of the 5th International Conference on Precision Agriculture, Bloomington, Minnesota, USA, 16-19 July, 2000. Pg 1-12; American Society of Agronomy; Madison; USA

Precision management of agricultural inputs such as herbicides for weed control is crucial to ensure profitable farms and long-term sustainability of the land. There is now a range of information tools that the farmers can avail themselves of, including yield monitors, global positioning systems (GPS), geographic information systems (GIS), variable rate technology (VRT), and hyperspectral remote sensing, all of which can be placed under the label of precision agriculture. This documentation addresses the effective, economical, and responsible integration of Hyperspectral remote sensing and precision agriculture technologies for use in small to medium sized farming operations for weed and herbicide management. In a test of the utility of such data, we have collected several inter-dependent data sets at an experimental farm on the eastern shore of Maryland, USA during the 1999 growing season, focusing on maize and soybeans. These data included: hyperspectral image data; ground feature differential GPS data; geo-located spectral measurements at ground level; and a database of field inputs and costs. Whether these technologies when used as weed and herbicide management tools can provide valuable information to a farmer for both short and long term decision making at a cost that is worth the investment remains a question. This paper describes the methods of data collection and analysis including preliminary results and lessons learned

Title: Use of GIS/GPS systems in IPM: progress and reality.
Authors: Ellsbury, M.M.; Clay, S.A.; Fleischer, S.J.; Chandler, L.D.; Schneider, S.M.; Kennedy, G.G. (ed.); Sutton, T.B.
Year: 2000
Source: Proceedings of Conference “Emerging technologies for integrated pest management: concepts, research, and implementation.”, Raleigh, North Carolina, USA, 8-10 March, 1999. Page 419-438; 38 ref.: American Phytopathological Society (APS Press); St. Paul; USA

The applications of geographical information systems (GIS) and global positioning systems (GPS) in integrated pest management (IPM) are discussed. The following topics are included: targeted sampling and area-wide management of insect pests; mapping, remote sensing, aerial, satellite and multispectral imagery of weeds; spatial variability, microclimates, soil spatial variability and economic thresholds of plant diseases; and factors constraining the adoption of emerging technologies in IPM.

Title: GIS Application in Weed Management System.
Author: Ho, Park Kwang
Year: 1998
Source: Kor. J. Weed Sci. 18: 4, pp. 356-363.

In general weed vegetation analysis has been applied to the study of weed population shift. However, it is a limited tool for understanding a problem region and a specific weed species in a certain area. Recently GIS has been used as an important tool to solve this problem or to conduct specific field analysis which enables to introduce a reasonable management strategy. Thus, the GIS study was carried out to understand and integrated weed population changes between 1981 and 1992 in Korea. The nationwide weed survey was performed through the whole rice paddy fields in 1981 and 1992. Weed occurrence was totally different over whole country based on these data. In 1981 a region with high weed occurrence was at western and central areas of Korea in terms of weed population density but this was changed into western and southern area in 1992. In both years there were high weed population density at Taean, Seosan county of Chungnam province in Korea. Thus, this particular area may be needed to introduce a special strategy to reduce weed population density and/or to control problem weed species.

Title: Multispecies resistance and integrated management: a bioeconomic model for integrated management of rigid ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*)
Authors: Monjardino, Marta; Pannell, David J. and Stephen B. Powles
Year: 2003
Source: Weed Science Vol. 51 : No. 5, pp. 798–809.

Rigid ryegrass and wild radish dominate and coexist throughout southern Australian dryland cropping regions. Widespread herbicide resistance in these species has led to adoption of diverse and complex integrated weed management practices, which require evaluation of their impact on farming systems. Therefore, a multispecies version of the bioeconomic model resistance and integrated management (RIM) has been developed to compare long-term economic and weed population outcomes of various integrated management scenarios. We have extended the original single-species ryegrass RIM model to include wild radish biology and additional weed management practices used to control this species. The multispecies model can be used to evaluate weed management scenarios for coexisting herbicide-resistant species by investigating the implications of different crop–pasture rotational sequences and of varying herbicide availability. Multispecies RIM shows that economic differences between the scenarios are not due to differences in weed densities but to differences in total weed control costs.

Title: Demography of the invasive shrub Scotch broom (*Cytisus scoparius*) at Barrington Tops, New South Wales: insights for management
Authors: Downey, P.O. and J.M.B. Brown
Date: October 2000
Source: Austral Ecology Vol. 25, issue 5. pp. 477-456

Abstract The exotic shrub Scotch Broom (*Cytisus scoparius*) has invaded large areas of eucalypt woodland at Barrington Tops, New South Wales, where it forms dense stands that have significant impacts on vegetation structure, flora and fauna. Data are presented from four 25 m 2 plots, which have been studied since 1985. Two plots were located in uniform broom thickets of different ages, and two were located across the margins of broom stands, which have since expanded to cover the entire plots. All broom plants in the plots (other than young seedlings, which were counted) were mapped, tagged and monitored annually. New seedlings appeared annually, but there was no relationship between their numbers (varying between years) and subsequent recruitment of older plants. The probability of seedlings reaching first flowering was less than 2%, and of surviving to mature size (>10 cm 2 basal area) was negligible. Seedlings mainly died through suppression (shade). Individuals less than 50 cm high were also browsed. Recruitment occurred only where light levels were high, either before closure of the broom canopy or after senescence had led to canopy opening. From approximately 12–30 years after initial invasion, broom stands underwent self-thinning of mature plants, accelerated by collapse of plants on to each other. Recruitment of new maturing plants after this period produced a stand that was less dense than that found after initial invasion. Broom is creating more disturbance-prone environments due to its impacts on other biota, likely alterations to the fire regime, and by harboring feral pigs. Further disturbance favors broom, and elsewhere it has resulted in massive seedling regeneration. While fire or other disturbance can be used to stimulate germination, and thereby reduce a large part of the soil seed bank, denser broom infestations are likely to result unless follow-up treatments can be applied over long time periods. A wiser management option, at least in the short term, may be avoidance of all disturbances, especially for stands of mature broom.

Title: Iowa Department of Transportation Integrated Roadside Vegetation Management Plan
Source: Iowa Department of Transportation
Weblink: http://www.iowalivingroadway.com/pdfs/IRVMPLANstate.pdf

The IDOT summarizes its roadside vegetation management plan in this three page document. Integrated Roadside Vegetation Management (IRVM) is a long-term approach to managing noxious weeds along Iowa's highways using a variety of treatments.

Title: Guide to Weed Control: 2004-2005
Source: Ontario Ministry of Agriculture and Food
Weblink: http://www.gov.on.ca/OMAFRA/english/crops/pub75/pub75toc.htm

This website will direct the reader to a table of contents for the manual, which are provide in .pdf format. Topics covered include; Principles of Integrated Weed Management, Application Technology, Precautions with all Pesticides, Preplant and Postharvest Weed Control, and Roadsides and Non-Crop Areas. Chapter 18, Roadsides and Non-Crop Areas, is a general overview of the Ministry's management techniques. A link is provided at the bottom of the page to a variety of information on weeds.

Title: Ecological strategies of shrubs invading extensified grasslands: their control and use.
Authors: Spatz, G.; Papachristou, T.G.; Papanastasis, V.P. (ed.); Frame, J. (ed.); Nastis, A.S.
Year: 1999
Source: Proceedings of the International occasional symposium of the European Grassland Federation, Thessaloniki, Greece, 27-29 May, 1999. Pg. 27-36; 24 ref.

Extensification of grassland is a result either of changing economic circumstances or increasing ecological awareness. Low-input grassland systems are normally of higher ecological value than high-input systems, but the trend is reversed as soon as extensification effectively results in inadequate grassland management. Generally, the existing grassland ecosystems in Europe are not natural, but have developed from forests and their irrational use by man and his domestic animals. Therefore any unnatural grassland ecosystem is kept in a balance by the management applied and will alter as soon as the management changes. Grassland tends to return to woody vegetation during plant succession. The stages of succession are of differing ecological value. Many studies show that biodiversity decreases as soon as shrubs take over open grasslands. Low grazing pressure is not able to withstand the invasion of shrubs, because many woody species are very well adapted to grazing and have developed special strategies for invasion into, and survival on, grasslands under grazing. After the establishment of shrubs, the microclimatic and soil factors soon change, creating an environment more favourable for further shrub succession. These changes can be detected by the use of Geographic Information Systems (GIS). In order to stop the succession of shrubs, the effectiveness of browsing/grazing by sheep and goats requires investigation. Woody vegetation has long been considered important for the nutrition of grazing animals in the Mediterranean region, particularly in those areas with a long dry season. They provide adequate amounts of green forage when herbaceous species are dry and all other forages are absent and this green material is the only source of nutrients during periods of drought. Therefore, several studies have been carried out examining the role of rangelands dominated by woody species as an important source of feed for grazing animals. Results of these studies suggest that an optimal forage supply is provided when wo ody and herbage components each cover about 50% of the rangeland. However, shrublands are mostly covered by dense woody vegetation with low levels of herbaceous vegetation and limited amounts of usable browse. In such densely wooded shrublands, a reduction of shrub cover with appropriate range management techniques is suggested as a method of optimizing forage, wood and livestock production.

Title: Roads as Conduits for Exotic Plant Invasions in a Semiarid Landscape
Authors: Gelbard, Jonathan L. and Jayne Belnap
Year: 2003
Source: The Journal of the Society for Conservation Biology, Volume 17 Issue 2, pp. 420

Roads are believed to be a major contributing factor to the ongoing spread of exotic plants. We examined the effect of road improvement and environmental variables on exotic and native plant diversity in roadside verges and adjacent semiarid grassland, shrubland, and woodland communities of southern Utah (U.S.A.). We measured the cover of exotic and native species in roadside verges and both the richness and cover of exotic and native species in adjacent interior communities (50 m beyond the edge of the road cut) along 42 roads stratified by level of road improvement (paved, improved surface, graded, and four-wheel-drive track). In roadside verges along paved roads, the cover of Bromus tectorum was three times as great (27%) as in verges along four-wheel-drive tracks (9%). The cover of five common exotic forb species tended to be lower in verges along four-wheel-drive tracks than in verges along more improved roads. The richness and cover of exotic species were both more than 50% greater, and the richness of native species was 30% lower, at interior sites adjacent to paved roads than at those adjacent to four-wheel-drive tracks. In addition, environmental variables relating to dominant vegetation, disturbance, and topography were significantly correlated with exotic and native species richness and cover. Improved roads can act as conduits for the invasion of adjacent ecosystems by converting natural habitats to those highly vulnerable to invasion. However, variation in dominant vegetation, soil moisture, nutrient levels, soil depth, disturbance, and topography may render interior communities differentially susceptible to invasions originating from roadside verges. Plant communities that are both physically invasible (e.g., characterized by deep or fertile soils) and disturbed appear most vulnerable. Decision-makers considering whether to build, improve, and maintain roads should take into account the potential spread of exotic plants.

Weed Control Measures

Weed control is an indispensable part of agricultural production as well as of vegetation management in agro-forestry. Weeds, often defined as undesirable plants in the wrong place, or simply as “plants out of place”, are a major problem to managers in various disciplines, including Departments of Transportation. Weeds are difficult to fully eliminate. Control measures are often expensive, their application impacting negatively on the surrounding environment, and may pose danger to applicators. Reportedly, significant portions of management expense incurred by road maintenance and management units may be attributed to weed management measures.

This section offers summaries of articles dealing with management of weeds which occur on roadsides. Further, highlights into impacts of the management activities on the surrounding environment, such as streams adjacent to treatment areas are discussed. Management practices discussed include mechanical, chemical and biological methods. Another alternative method of weed control reported on is that of hot water treatment.

Topical coverage in this section includes publications presenting results of evaluation studies on:
- Effectiveness of herbicides in the treatment of roadsides infested with specific weed species
- Effects of different mowing regimes on the non-native and invasive perennial grasses
- Effectiveness of Variable-rate Technology (VRT) herbicide application systems
- Comparisons of herbicide treatments calculated using ‘a decision algorithm for patch spraying’

Title: Herbicides help Illinois DOT control roadside weeds
Author: Caylor, Peggy
Date: March 1998
Source: American City & Country

This article reports on the IDOT’s use of mechanical and chemical methods to control roadside vegetation. The Department concluded that though mowing is effective to manage grasses, it merely delays problems with larger vegetation types. Along the 4,700 miles of roads IDOT maintains, there grows a variety of weed species; this includes Canada thistle, musk thistle, teasel, and locust. In order to control these species, and to protect a variety of ornamental plants which are also found along Illinois highways, the agency uses several compounds, including Garlon 3A. This chemical, manufactured by Dow Agro Sciences, effectively controls teasel and thistle, but is not 'soil active'; it does not leach into soil to be absorbed by other plants. In addition to Garlon, IDOT uses Tordon 101M to control thistle and teasel, and utilizes a truck-mounted broadcast application method for large areas. The cost of herbicide use is about $15 per acre; whereas mowing operations cost approximately $30 per acre.

Title: Control of musk thistle (*Carduus nutans*) with Transline® and Escort® along roadsides
Authors: Meyer, Robert E.; Simpkins, Cynthia L.; McCully, WayneG.; and Steven G. Evans
Date: March 1994
Source: Texas Transportation Institute

In this study, the herbicides Escort® (metsulfuren methyl) and Transline® (clopyralid) were evaluated for their effectiveness in the treatment of roadsides infested with musk thistle. Treatment areas consisted of three separate plots, which were sprayed once between February and April 1992. The treated plots were assessed at one, two and three months following spraying. It was found that Transline caused yellowing and curling of leaves and stems one month following treatment. At two months post treatment, almost all thistles were killed. The dosage of Transline used for the three areas was: 389, 779, and 1029 ml/ha. It was also found that the herbicide effectively prevented further musk thistle invasions in subsequent years. Escort® was used on three additional plots at dosages of 35.0, 52.5, and 70.0 g/ha. This product effectively killed nearly all thistles on the plots at two months following treatment. However, after three months small thistles appeared at all locations. Further, it was observed with the use of both of these herbicides that many native plants, such as prairie coneflower, were eradicated from the sites.

Title: Progress report on research to identify effective foliar spray and mechanized spray delivery systems for the selective control of mesquite on rights-of-way
Authors: Ueckert, Darrell N. and Allan W. McGinty.
Date: March 1998
Source: Texas Department of Transportation

The study tested high volume foliar sprays with a mixture of 0.5% clopyralid and 0.5% triclopyr ester surfactants. Delivery methods included: a "Brush robot", which was equipped with spot guns that sprayed plants with 120 kPa of herbicide as the machine's sensors detected a weed; "mesquite-sensing booms" sensed plants using horizontal beams of modified light, and dispersed herbicides through automated rollers (made of PVC pipe and carpet) attached to a tractor; a weed sprayer attached to an ATV, which was used as the operator detected mesquite plants. Success rates for these methods averaged 93%, and regression analysis of associated operating costs were included.

Title: Herbicide use in the management of roadside vegetation, Western Oregon 1999-2000: effects on the water quality of nearby streams
Author: Wood, Tamara M.
Source: U.S. Geological Survey, in cooperation with the Oregon Department of Transportation (ODOT)

This study was conducted to detect the presence or absence of herbicides in streams adjacent to ODOT treatment areas. Herbicides frequently used by ODOT include Krovar (diuron and Bromacil), Oust (sulfometuron-methyl), and Roundup (glyphosphate). It was estimated that very little glyphosphate would be detected, as it is hydrophobic. Further, it was assumed that sulfometuron-methyl would be detected in trace amounts, because it is normally applied at very low rates. In this case, sulfometuron-methyl is generally applied by the ODOT at 20% of the rate of diuron and Bromacil application. The study was conducted in two phases, designed to examine the transport of herbicides from road shoulders under both natural and controlled precipitation. Small test plots were established along roads, and herbicides were applied at the standard ODOT rates. Rainfall was then simulated one day after herbicide application, and again at weeks one and two. In this phase, it was found that the greatest runoff concentration was sulfometuron-methyl, with diuron and glyphosphate a distant second. The second phase of data was conducted from October of 1999 through January 2000, and measured runoff rates under natural rainfall conditions. In this case, diuron concentrations ranged from 1-10 μg/L in an adjacent stream, and sulfometuron-methyl was detected in concentrations of 0.1-1.0 μg/L during the three month study period. The study concluded that the greatest runoff would occur shortly after herbicide application, under very heavy storm events. Results indicated that ODOT spraying accounted from concentrations close to the 90 percentile of diuron and Bromacil. Further, diuron and Bromacil and sulfometuron-methyl were still detectable in runoff more than three months after application, though in concentrations less than 1 μg/L.

Title: Controlling invasive *Arrhenatherum elatius* and promoting native prairie grasses through mowing
Authors: Wilson, Mark V., and Deborah L. Clark
Date: June 2001
Source: Applied Vegetation Science Vol. 4, issue 1. pp. 129-139

Abstract. Control of invasive plants is a key element of conservation and restoration efforts. We report results from a five-year field experiment in western Oregon, USA that evaluates the effects of different mowing regimes on the non-native and invasive perennial grasses *Danthonia californica* and *Festuca roemeri*, and groups of other native and non-native grasses and forbs. Eight treatments were designed to test hypotheses about the role of mowing height and time of application on the plant community.
Differences among treatments emerged only after two or three years of treatment. This delay in response reinforces the need for long-term studies. Annual mowing was most effective at reducing *Arrhenatherum* cover and flowering when applied in late spring or early summer, the time of *Arrhenatherum* flowering and expected maximum above-ground allocation. Double mowing and mowing at 15 cm. Were more effective in reducing *Arrhenatherum* cover than were single mowing and mowing at 15 cm. All treatments increased the cover and flowering of *Danthonia*. Statistical model analysis showed that increases in cover and flowering of the native grass *Danthonia* were caused by its release from suppression by *Arrhenatherum*. Four years of the most effective treatment, mowing at 15cm. in late spring, converted an *Arrhenatherum*-dominated site to a prairie dominated by native grasses. This is one of the few documented cases of pest control causing an increase in native plant abundance. These results show that mowing, properly applied, can be an effective tool for restoring degraded, *Arrhenatherum*-dominated prairies.

Title: Foreign Agents Imported for Weed Control
Authors: Stelljes, Kathryn Barry and Marcia Wood.

Date: March 2000
Source: Agricultural Research, Vol. 48, issue 3. pp. 4-10

The article describes biological control research conducted at the Agricultural Research Service's Western Regional Research Center in Albany, California. Of particular interest to researchers at the Center are invasive plant species such as leafy spurge, saltcedar, and melaleuca. To combat these vigorous and wide-spread plants, the Center imports insects from the plants' native lands in Europe and Asia. Most effective at controlling leafy spurge appear to be 4 varieties of flea beetles of the genus *Aphthona*, which have been introduced in 50 counties of seven states. The beetles burrow into the roots and feed on the leaves of spurge, while exposing the plant to fungi and bacteria. Another predator of leafy spurge, the shade-loving gall midge *Spurgia capitigena*, is to be introduced in cooler, moist areas. Also of interest to researchers at the ARS is a leaf beetle, *Diorhabda elongata,* and *Trabutina mannipara*, a mealybug. These species are the natural enemies of saltcedar (*Tamarix* spp.), an extremely invasive shrub found in riparian zones throughout the western US.

Title: Effect of Leafy Spurge (*Euphorbia esula*) Genotype on Feeding Damage and Reproduction of *Aphthona* spp.: Implications for Biological Weed Control
Authors: Lym, Rodney G., and Robert B. Carlson
Date: February 2002
Source: Biological Control, Vol. 23, issue 2. pp. 127-133

Since the 1980's, six varieties of flea beetles (*Aphthona* spp) have been introduced nationwide to control the invasive, non-native plant, leafy spurge (*Euphorbia esula).* The adult insects emerge from May to early July and begin feeding on leafy spurge foliage. Larval beetles burrow into root tissue of leafy spurge, causing extensive damage and allowing for the establishment of various pathogens. Beetle variety varies from region to region, based on effectiveness, which has been attributed to a variety of causes. Though environmental parameters (slope, vegetation, soil type and moisture) most likely have a substantial influence on the success of the beetle variety, researchers have begun to attribute some success variability to differences in the genotypes of the hosts. For example, while genotypes of leafy spurge found in North America are most similar to those found in Russia, biological control agents used thus far (i.e. *Aphthona, Spurgia* spp.) are native to western Europe. This study was designed to closely match host plant and insect as closely as possible. The research also indicated that soil type variation clearly influences the beetles' success, because leafy spurge rooting patterns vary in sandy, silty, and loamy soils.

Title: Development of a herbicide application map using artificial neural networks and fuzzy logic
Authors: Yang, Chun-Chieh; Prasher, Shiv O.; Landry, Jacques-Andre and Hosahalli S. Ramaswamy
Date: May 2003
Source: Agricultural Systems, Vol. 76, issue 2. pp. 561-574

Precision agriculture has grown in popularity, in part due to its efficiency and to the reduced impacts it has on surrounding ecosystems as compared to conventional agriculture. Agricultural researchers have begun using advanced technologies, such as remote sensing to detect the distributions and densities of various plant communities. This article describes the use of fuzzy logic as it applies to agricultural practices. Fuzzy logic was first utilized for farming in the mid 1990s, and is here applied to precision agriculture with the development of an algorithm for controlling herbicide applications. Combined with an Artificial Neural Network (ANN), which classified weeds and crops by leaf shape and color, the algorithms allowed researchers to develop an accurate herbicide application map.

Title: Does kriging predict weed distributions accurately enough for site specific weed control?
Authors: Rew, R.J., Whelan, B., and A.B. McBratney
Date: 2001
Journal: Weed Research, Vol. 41, issue 3. pp. 245-263

Numerous studies have demonstrated the patchy distribution of weeds within fields. The majority of these studies have used discrete sampling, recording weed densities at the intersections of regular grids. In this study, *Avena* spp. seedlings were recorded on square grids at four sites. The data were then divided into test and real data sets using the whole, two-thirds and one-half of the data to evaluate the consistency of global variogram models and accuracy of ordinary kriging estimates. Kriging provided poor weed density estimates at both very low and high densities, i.e. data were smoothed when compared with true values. Grid sampling took considerable time and, therefore, money to complete, whereas continuous sampling with multispectral imagery (performed at one site) was much quicker and at a finer resolution. It is suggested that sampling systems that collect continuous rather than discrete data are currently more appropriate for site-specific weed management.

Title: Development of a sensor-based precision application system
Author: Tian, Lei
Date: November 2002
Source: Computers and Electronics in Agriculture; Vol 36, issue 2/3. pp. 133-149

The smart sprayer, a local-vision-sensor-based precision chemical application system, was developed and tested. The long-term objectives of this project were to develop new technologies to estimate weed density and size in real-time, realize site-specific weed control, and effectively reduce the amount of herbicide applied to the crop fields. This research integrated a real-time machine vision sensing system and individual nozzle controlling device with a commercial map-driven-ready herbicide sprayer to create an intelligent sensing and spraying system. The machine vision system was specially designed to work under outdoor variable lighting conditions. Multiple vision sensors were used to cover the target area. Weed infestation conditions in each control zones (management zone) were detected rather than trying to identify each individual plant in the field. To increase the delivery accuracy, each individual spray nozzle was controlled separately. The integrated system was tested to evaluate the effectiveness and performance under varying commercial field conditions. Using the onboard differential GPS, geo-referenced chemical input maps (equivalent to weed maps) were also recorded in real-time.

Title: Precision offset spray system for roadway shoulder weed control
Authors: Slaughter, D.C., and D.K. Giles
Date: July/August 1999
Source: Journal of Transportation Engineering, Vol. 125, issue 4. pp. 364-372

A precision offset spray system was developed for use by highway maintenance Departments for the control of unwanted vegetation in the graded shoulder area adjacent to roadways. The offset

sprayer consisted of two fundamental elements: (1) A machine vision system; and (2) a rapid response intermittent spray system.
This study showed that it is feasible to use machine vision on a moving vehicle to automatically detect the presence of green plant material and to apply herbicides exclusively to plants and not to nonplant materials (e.g., bare soil). The system substantially reduced the amount of herbicide applied to nonplant material. In
system tests, there was up to a 97% reduction in applied spray mix over conventional continuous spray applications with a plant deposition rate of 57% of continuous spray systems. Implementation of this technology would allow highway maintenance Departments to reduce the cost of weed control and the amount of chemical herbicides released into the environment, while maintaining current levels of weed control efficacy.

Title: Effect of Herbivore Density, Timing of Attack and Plant Community on Performance of Creeping Thistle *Cirsium arvense* (L.) Scop. (Asteraceae)
Authors: Bacher, S., and F. Schwab
Date: June 2000
Source: Biocontrol Science and Technology, Vol. 10, issue 3. pp. 343-352

The article discusses control alternatives for the problematic and widespread weed, *Cirsium arvense*, creeping thistle and the use of a shield beetle, *Cassida rubiginosa* to control the thistle. In many European organic farming systems, fallow areas are included within the tilled agricultural fields. These so-called ecological compensation areas make up about 5% of the total farm areas and are either left fallow for any existing seeds in the soil to sprout, or are seeded with desirable herb species after tillage. This system is designed to repress weeds, and to prevent the spread of the problematic weeds into neighboring agricultural fields. Creeping thistle is often present in the two described systems. In this field experiment, Bacher and Schwab evaluated the effectiveness of herbivory by *C. rubiginosa* on the control of *C. arvense*. During the experiment, a mortality rate of 50% occurred in *C. arvense* where beetle populations were high. Further, the second cohort of *C. rubiginosa* appeared to have a more pronounced impact on the primary stem height of the thistles, most likely due to the beetles' faster rate of development later in the summer. Overall, the study suggests that an integrated approach to weed control is necessary, and includes careful timing of the release of biological control agents, tillage systems, and climatic considerations.

Title: Influence of mechanical cutting and pathogen application on the performance and nutrient storage of *Cirsium arvense*
Authors: Kluth, Stephanie; Kruess, Andreas; and Teja Tscharntke
Date: April 2003
Source: Journal of Applied Ecology, Vol. 40, issue 2. pp. 334-344

This study examined the effective of a comprehensive system of weed control of *C. arvense* using mechanical and biological control techniques. According to Kluth et al., it has been established that mechanical treatments alone are not effective in controlling large quantities of *C. arvense*, due to the plant's deep root system and its tendency to dominate other herbaceous plant species in a meadow ecosystem. To deter the thistle from producing viable flowers and seeds, the rust *Puccinia punctiformis* was applied to thistles following mechanical treatment. Systemically infected plants are prevented from flowering and display high rates of premature mortality. By the second year of the study, the combined cutting and pathogen treatments effectively reduced the number of viable flower heads to 9% of the test group. This displays how a combination of control treatments increases overall effectiveness.

Title: Competitive control of invasive vegetation: native wetland sedge suppresses *Phalaris arundinacea* in carbon-enriched soil
Authors: Perry, Laura G., Galatowitsch, Susan M., and Carl J. Rosen
Date: August 2004
Source: Journal of Applied Ecology, Vol. 41, issue 8. pp. 151-162.

The article provides an alternative method to many traditional chemical and mechanical methods of weed control; instead of temporarily treating a small number of individuals, the researchers opted to manage an entire ecosystem to reduce its vulnerability to invasion. It has been observed that non-native grasses frequently inundate sedge meadow systems in North America. Species of interest in this study included the native sedge *Carex hystericina*, which was manipulated to suppress the invasive grass *Phalaris arundinacea.* The species were observed in a greenhouse setting, and were cultivated in soil with varying nitrogen concentrations (25-400 mg/kg). Lower levels of available nitrogen were attained by using carbon enrichment, and were mitigated by creating a nutrient gradient using NH4-N. It was found that competition between the two species was greatly impacted by carbon additions; in situations with no carbon additions, mean *Carex* (monoculture) biomass was greatly reduced, and mixtures of *Carex/Phalaris* produced biomass ratios of 1:5. Clearly, the non-native grass readily out competes the native sedge. In contrast, scenarios in which carbon was added yielded substantial reductions in *Phalaris* biomass.

Title: Effect of air temperature, rain and drought on hot water weed control
Authors: Hansson, D., and J. E. Mattsson.
Date: August 2003
Source: Weed Research, Vol. 43, issue 4. pp. 245-251.

This study examined another alternative method of weed control: that of hot water treatment. Hot water weed control is most favorable when used in hard surface areas, and in regions where pesticide use is prohibited. The effectiveness of this treatment is greatest when used on annual and young perennial plants, such as *Sinapis alba* (white mustard), as was used in this experiment. Researchers compared the survival rates of young mustard plants subjected to treatments using two different water temperatures, as well as the effect of other factors (water stress, hot and cool air temperature) preceding treatment. Researchers found that increased air temperatures during treatment lead to greater transpiration rates in the plants, thus increasing the capacity of the individual to cool itself. In addition, plants that had been watered prior to treatment (simulating rain) required significantly higher energy levels (+21%) to attain the same 90% reduction in fresh plant weight as the dry subjects. The effectiveness of hot water treatment was increased when the plants were water-stressed, as compared with the fresh weights of individuals that had been watered regularly.

Title: A decision algorithm for patch spraying
Authors: Chistensen, S., Heisel, T., Walter, A. M., and E. Graglia
Date: August 2003
Source: Weed Research, Vol. 43, issue 4. pp. 276-284.

This Danish study compared herbicide treatments calculated using 'a decision algorithm for patch spraying' (DAPS) with the Danish decision support system, PC-Plant Protection. The DAPS system consists of a competition model, an herbicide dose-response model, and an estimation (algorithm) of the most economically favorable herbicide dose. The primary difference between these two systems is that DAPS incorporates a crop-weed competition element. In this five-year experiment, barley was grown in plots of 24m x 46m that were further divided into 12m x 12m subplots. Each larger plot was designated as control, PC-Plant Protection (herbicide and dosage were determined using decision support software), DAPS (site-specific herbicide treatments), or Mean DAPS (in which the herbicide dose was calculated using DAPS on a per plot basis). The control plots were not treated with herbicide in the first two years of the experiment, and were treated in subsequent seasons using label-recommended doses of herbicide. The results of the study showed that there were no major differences in yield between PC-Plant Protection vs. DAPS and DAPS vs. mean DAPS. Further, DAPS and mean DAPS provided significantly higher fiscal returns because these systems called for much lower herbicide doses than PC-Plant Protection.

Title: Performance study of variable-rate herbicide applications based on remote sensing imagery
Authors: Thorp, K.R.; and L.F. Tian
Date: 2004
Source: Biosystems Engineering, Vol. 88, issue 1. pp. 35-47

This study was designed to determine the effectiveness of Variable-rate Technology (VRT) herbicide application system. Researchers used three rates of application (100, 67, and 33%) in a heavily weed-infested soybean plot. Three blanket applications were also tested. Results indicate that VRT is the preferable method, as it was most effective and most efficient in herbicide application. However, it was also determined that low rates with VRT were found to be inadequate in controlling weed populations, and that medium and high rates performed comparably well-indicating that unnecessarily high doses were used in some areas of high weed density.

Weed Management by DOTs in select States

Presented under this section are summaries of publications and reports on weed management activities undertaken by various United States Departments of Transportation units. Articles addressed here include various reports and journal publications on past and current research findings on best management practices for control of weeds in roadsides. Future trends in management of roadside vegetation are also discussed. These include discussions on current and future trends of chemicals use in weed control.

Also reported are results of studies on species tolerance to specific herbicides. Methods that could significantly lower the required mowing and other mechanical control of roadsides are discussed. Included here is a summary of a paper on Forest Service proposals to authorize Departments of Transportation to use herbicides which are registered by the U.S. Environmental Protection Agency, as part of an annual vegetation management program along public highways that pass through National Forest System lands.

Title: Survey Results: How DOTs Control Vegetation
Year: 1997
Journal: Better Roads, Vol: 67 Issue 9, pp.19-20

Vegetation managers and maintenance supervisors were surveyed by Better Roads' editors as to their chemical and mechanical mowing practices, equipment, and where the future of vegetation management is headed. Survey responses indicate fewer chemicals are being used, more labor is being outsourced, and more native plant species are being used to naturalize roadsides. Chemical companies are providing more environmentally friendly herbicides to meet new changes in regulations. A number of the top DOT chemical choices are Group E -- said to be virtually non-toxic -- compounds, having the safest EPA designation.

Title: What's Ahead for Roadsides?
Author: Keating, Janis
Source: Erosion Control
Weblink: http://www.forester.net/ec_0109_what.html

This online article provides an overview of several states' methods of weed control, and the effectiveness of each. Some states, like Texas and Florida, primarily use mechanical means to reduce weed populations, while others, such as Arkansas and Michigan avoid mowing for ecological reasons. Select biocontrol methods are also briefly covered for Leafy Spurge and Purple Loosestrife.

Title: Roadside Management Trends in Minnesota - 1973 To 1997
Authors: Varland, K.L.; Schaefer, P.J.
Year: 1998
Conference Title: International Conference on Wildlife Ecology and Transportation, Fort Myers, Florida. pp. 214-228
Corporate Source: Federal Highway Administration, 400 7th Street, SW, Washington, DC , 20590,

Minnesota's Roadsides for Wildlife (RFW) Program was initiated in 1984 to (1) promote roadside habitat awareness, (2) reduce spring/summer roadside disturbance, and (3) improve quality of roadside habitat. Special roadside management surveys completed in 1973 and 1983 indicated that roadside disturbance was negatively impacting wildlife habitat on more than 40% of roadsides. Each August, since 1984, the RFW Program conducted a management survey that coincides with the Minnesota Department of Natural Resources (DNR) roadside wildlife counts to measure the Program's impacts and determine management trends. Roadside mowing dominated roadside disturbance. Disturbance has averaged a 19% decline impacting 42,450 ha since the beginning of the Program. A 1985 roadside mowing law has resulted in reduced roadside mowing. Weather is also a factor. Undisturbed roadside vegetation has remained relatively stable since 1987. The greatest reductions in roadside disturbance have occurred in east-central and west-central regions. The peak of mowing activity during summer has remained the same since 1984 with about 80% occurring during July 1-31. Other disturbance factors (lawns and agricultural encroachment) have increased in east-central, south-central, and west-central regions. Poor quality nesting cover remained relatively stable from 1992-97 and averaged about 16% of roadsides surveyed. Good quality cover increased from 25% to 45% and moderate quality cover declined during this period. A public relations approach to roadside management has brought about changes in legislation, mowing behavior, and greater participation by road authorities. Future Program emphasis will include integrated roadside vegetation management and increased use of native prairie vegetation.

Title: Controlling Leafy Spurge And Canada Thistle By Competitive Species. Final Report
Authors: Biesboer, D.D.; Darveaux, B.; Koukkari, W.L.

Date: 1994
Report No: MN/RC-94/32; 93p
Publisher/Corporate Author(s):
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Minnesota Department of Transportation, Office of Research Administration, 117 University Avenue, St Paul, MN 55155 USA

A study was performed to assess the use of perennial native grasses in the control of leafy spurge and Canada thistle and also to evaluate the effects of herbicides applied during the fall to leafy spurge crown buds. As part of an integrated vegetation management program, grass treatments containing the native prairie grass little bluestem established well and were effective at reducing the cover of leafy spurge. Paramount to the success of using native grass species is getting adequate grass establishment which necessitates the careful selection of grass species adapted to the specific site conditions. A fall application of the herbicide *picloram* at 0.5 and 1.0 lb per acre was very effective at controlling leafy spurge and may be mediated via the direct absorption of *picloram* by the elongated crown buds at this time. The report contains an extensive literature review of the biology and weed control efforts of both leafy spurge and Canada thistle.

Title: Innovative Herbicide Sprayers for Roadsides, Slopes and Ditches (Final Report)
Author: Toussaint, C.
Date: February 1997
Publication Report No.: MN/PR-97/08, 30p; Minnesota Dept. of Transportation, St. Paul. Office of Maintenance Operations

The Minnesota Department of Transportation (Mn/DOT) has been active in developing the best technology for roadside vegetation control. One method, herbicide spraying, helps eliminate unwanted vegetation. Treatment of unwanted weeds often requires the use of different herbicides. Sprayers must have the capacity to spray more than one chemical at a time, negotiate rough terrains, and apply herbicides safely and in a way that preserves the environment. This report presents the results from testing and evaluating four automated sprayers: The B&B Ditch Sprayer 300 Prototype, a Wanner Innovative Sprayer, the Micro-Track Spray System, and the SCS 750. All four tested sprayers are more economically feasible that the traditional sprayer. The B&B Ditch Sprayer has the lowest net annual savings of the four tested sprayers. The Wanner Sprayer is more economical for use in large Districts or in areas with extensive road miles. The Micro-Track Sprayer has the highest rate of return, and also reduces annual costs. The SCS Sprayer has the highest net annual savings and also can monitor, tabulate, and print all vital statistics. The report details product features, testing, and results.

Title: Increased Options for Weed Management in the North Carolina Highway Wildflower Program
Authors: Yelverton, F.H.; Warren, L.S., Jr
Date: October 2002
Report No: FHWA/NC/2002-020; Final Report; 75p

The North Carolina Department of Transportation (NCDOT) has implemented a highway wildflower program that now encompasses 3500 roadside acres throughout the state. Methyl bromide has become essential in establishing these beds. However, the Environmental Protection

Agency (EPA) has classified methyl bromide as an ozone depleting substance and has banned production in 2005. Research was conducted 1) to determine if wildflowers could be established and maintained using preemergence (PRE) and/or postemergence (POST) herbicides, 2) to evaluate the efficacy of these herbicides on native vegetation, and 3) to evaluate the efficacy of nonchemical weed control options such as cover crop plantings. Twenty-one PRE and 20 POST herbicides were evaluated on 29 wildflower species in 3 greenhouse and 2 field trials. In general, wildflowers were more tolerant to the PRE herbicides. However, no herbicide came close to methyl bromide in relation to safety and tolerance to all wildflower species. Field personnel must be able to select species based on weed presence and the herbicides needed to control those specific weeds without injuring the wildflowers. Based on NCDOT surveys, the 3 most problematic weeds throughout the state are vetch species, curly dock and Carolina geranium. These weeds were controlled PRE and also POST with Cotoran 4L, Sinbar 80WP and Velpar 75DF. However, only limited wildflower species displayed tolerance to these herbicides. None of the 29 species evaluated have tolerance to Velpar 75DF applied POST, so this treatment is not an option. Ox-eyed daisy (mature plantings of 1 year or more) and spurred snapdragon were the only wildflower species with POST tolerance to Sinbar 80WP. Greenhouse trials were initiated to see if covercrop plantings would control weeds. Rye, wheat and oats were tested on 12 weed species. None of the weeds were completely controlled but dry weights were reduced in hairy vetch in 2 of 2 trials. Dry weights were reduced in common lambsquarter, curly dock, redroot pigweed, wild mustard, spiny sowthistly and Carolina geranium in 1 of 2 trials. Covercrops should not be considered a substitute for herbicides for weed control in wildflower beds.

Title: Increased Options for Weed Management in the North Carolina Highway Wildflower Program
Project Number: HWY-99-12
Author: Fred Yelverton and Harold Coble, Department of Crop Science, North Carolina State University Year: 2002
Source: http://itre.ncsu.edu/cte/rip_vegemgmt.html - *Final Report*: in progress

The purpose of this project was to develop methods of controlling unwanted vegetation in the roadside wildflower program without using methyl bromide. The North Carolina Department of Transportation has been successful in establishing non-native wildflower species on rights-of-way by using methyl bromide, a broad spectrum soil fumigant effective in killing both growing plants and seeds of most plant species. Methyl bromide is used at relatively high rates of application, up to 400 pounds per acre. Since methyl bromide is a gas, it slowly escapes into the atmosphere once the plastic cover used to keep it in place is removed. The problem with that is that the bromide ion that is released reacts with ozone and may result in depletion of the earth's protective ozone layer. Therefore, the United States Environmental Protection Agency has issued a ban on methyl bromide manufacture and use in the United States effective in the year 2005, with significant use reductions scheduled before that time. If the wildflower program is to be a continued success, new technologies must be found to provide weed control in the establishment phase as well as the maintenance program for those beds already established.

Title: Vegetation Management Section: Maintenance Programs, Weed Management
Author: State of North Carolina, Department of Transportation
Source:
http://www.doh.dot.state.nc.us/operations/dp_chief_eng/roadside/vegetation/maintenance/weed.html

Stationary objects such as guardrails and sign posts must remain clear of unsightly vegetation in order to serve their purpose. Pre-emergence and post-emergence herbicide treatments may be utilized to prevent weeds and brush from growing around these structures. When planning such a program, care should be taken to select herbicide materials that will not cause complete bare-ground conditions which could lead to erosion control problems. This planning is especially needed in areas of increased drainage. The Department is currently encouraging the establishment of low growing turf such as centipede under guardrails, to reduce erosion and weed growth. Centipede's allelopathic effect should reduce the need for future herbicide applications.

Title: Low Maintenance Turfgrass and Management Systems for N.C. Roadsides
Authors: Bruneau, A.; Yelverton, F.; Cooper, R.; Johnson, C.
Year: 1999
Corporate Source: North Carolina State University, Raleigh, Department of Crop Science, Box 7620, Raleigh, NC, 27695-7620, North Carolina Department of Transportation, P.O. Box 25201, 1 South Wilmington Street , Raleigh, NC, 27611, Federal Highway Administration, 400 7th Street, SW, Washington, DC , 20590,
Report Number: FHWA/NC-99-007, Final Report; 40p

This project indicated several potential methods that could significantly lower the required mowings of roadsides. The adaptability trials resulted in three cool season and two warm season species being recommended. The cool season species include turf type tall fescue, fine fescue, and bentgrass. Turf type fescue seed head production was as vigorous as Kentucky-31 during the spring of the year, however, turf type tall fescues ultimately required two fewer mowings than Kentucky-31 by year end. Fine fescues were recommended for their continued use in mixtures, especially in shaded regions. Bentgrass performed well under low maintenance conditions and required only one mowing for the year. Recommended warm season species include common bermudagrass and centipedegrass. Common bermudagrass demonstrated a vigorous establishment rate, requiring only two mowings for the year. Due to common bermudagrass' lack of cold tolerance it was only recommended for the Piedmont region of the state. Centipedegrass, while slow to establish from seed, demonstrated excellent survival under the low maintenance conditions of the project. Spring establishment from seed was crucial in surviving the first winter. Seeding centipedegrass was only recommended for the Piedmont region of the state.

Title: Environmental Assessment for Management of Noxious Weeds and Hazardous Vegetation on Public Roads on National Forest System Lands
Author: USDA Forest Service Southwestern Region, cooperating with U.S. Department of Transportation, Federal Highway Administration, Arizona Division
Source: http://www.fs.fed.us/r3/projects/ro/ea-noxiousweeds/abstract.html

The USDA Forest Service, Southwestern Region, proposes to authorize the Arizona Department of Transportation (ADOT) to use U.S. Environmental Protection Agency-registered herbicides as part of an annual vegetation management program along public roadways that pass through National Forest System lands throughout Arizona. The objectives of the proposal are to (1) contain, control, or eradicate noxious weeds that are spreading from highway and road easements onto adjacent forests and rangelands; and (2) control vegetation that presents safety hazards to drivers using public roadways. Public roadways include interstate highways, Federal highways, and State roads. The Federal Highway Administration (FHWA) has the authority to approve herbicide use for all or

portions of interstates, U.S. highways, and some State highways under U.S. Department of Transportation (USDOT) easements within the boundaries of the Apache-Sitgreaves, Coconino, Coronado, Kaibab, Prescott, and Tonto National Forests. Approval by a Forest Service official is required for the proposed use of herbicides on easements not authorized by the FHWA and in a 200-foot strip outside of USDOT easements on each side of and along other public roadways. Treatment of the 200-foot strip could be needed where noxious weed infestations extend outside the road easement. The objective of such a treatment would be to maintain the integrity of a site-specific noxious weed control operation.
Authorization to use herbicides would be provided to ADOT based on an annual work plan with each national forest prior to implementation of annual treatments. This proposal would provide the opportunity for the Forest Service, FHWA, and ADOT to coordinate treatment schedules to provide, to the extent possible, alternate routes of travel for individuals with multiple chemical sensitivity(MCS).
Throughout the State, ADOT has responsibility to manage vegetation along about 6,000 miles of highways, which includes about 378,000 acres of rights-of-way. About 2,700 miles (170,100 acres) pass through National Forest System lands. It is estimated that about 5,000 acres could be treated with herbicides on an annual basis. Aerial application of herbicides will not be considered.

Title: Dead Weeds On the Side of the Road
Author: Government Technology; California Department of Transportation
Year: 1995
Source: http://www.govtech.net/magazine/gt/1995/nov/dead_wee.php

Among the human endeavors that call for high technology, killing weeds seems to rank in the lower strata. Yet weeds are exactly what the California Department of Transportation (CalTrans) is targeting with its latest application of technology. Department officials have leased an innovative sprayer that uses computer technology and advanced optics to determine whether a weed is present. If so, the sprayer triggers the appropriate nozzle and the weed is sprayed. If not, the machine passes over the ground without firing. The result is that only weeds are sprayed, not bare ground. The savings in chemical usage can be tremendous. That's important not only from a budgetary standpoint, but also in helping the Department meet its goal of cutting chemical use by 50 percent by the year 2000 and by 80 percent by 2012

Title: Herbicide Use, Weed Control and Roadside Maintenance
Author: Washington State Department of Transportation
Source: Washington State Department of Transportation
Weblink: http://www.wsdot.wa.gov/traveler/roadsidemaintenance.htm

This site provides an overview of the methods and tools used by the WSDOT for the control of noxious weeds along state rights-of-way. The agency reports that it typically uses 3.8 lbs/acre of the herbicide 2,4D, or “Weed ‘n Feed”. 2,4D is one of the most commonly used herbicides. The compound effectively kills broadleaf plants such as dandelions, and is utilized by homeowners, golf courses, schools, and others. WSDOT reports that it has reduced its use of herbicides by decreasing the ‘roadside spray line’ from eight feet to three feet since 1994. The agency also notes that it would cost an additional $2.4 million for five counties to convert to non-herbicide control methods. The site also provides links to the State Noxious Weed Control Board, information on highway maintenance, and to Washington’s Highway Landscaping/Roadside Planting program. The last of these is an Integrated Pest Management approach to weed control along roadways, and follows the state's Roadside Classification Plan as its maintenance standard.

Title: Island County Roadside Maintenance and Weed Control
Author: Washington State Department of Transportation
Year: 2004
Source: http://www.wsdot.wa.gov/maintenance/pdf/island_county.pdf

The Washington State Department of Transportation (WSDOT) maintains 50 miles of highway (Highway 20 and Highway 525) on Whidbey Island and 3 miles of highway (Highway 532) on Camano Island. We recently proposed changes to the way we maintain roadside plants and weeds on these highways. We provided a draft plan to the public and, after listening to suggestions and questions, revised it. The revised plan will be published on WSDOT's Web site on Friday, May 7, 2004. The following information summarizes the revised plan and WSDOT's latest approach to roadside maintenance on Whidbey and Camano Islands.
WSDOT will:
· reduce herbicide use by approximately 60 percent on Whidbey and Camano Islands in 2004 compared to the average annual use for the past three years
· quit using the herbicide diuron on Whidbey and Camano Islands
· very strictly limit herbicide use on over 23 miles of highway, including an 18 mile stretch of highway on south Whidbey Island and all of Highway 532 on Camano Island. In these areas we shall eliminate the annual spring herbicide application on the three-foot section of shoulder nearest the highway and allow grass to grow up to the edge of the road surface
· continue to expand use of techniques including mowing, hand pulling and planting native plants
· work with independent experts from the University of Washington to evaluate alternative maintenance practices

Title: California Communities Wage New Kind of War on Roadside Weeds
Author(s): Public Works Journal Corporation
Year: 2002
Source: Public Works, Vol. 133 (13): pp. 22-25

The State of California is leading the way toward new policies in roadside weed management that do not rely as heavily on mowing and spraying, because of environmental concerns and budget and safety constraints. The California Department of Transportation (Caltrans) is seeking to reduce herbicide spraying by 80 percent by the year 2012 and has already met an earlier goal of cutting herbicides by 50 percent from 1992 levels. New machines make herbicide application more precise, reducing waste, exposure by workers and runoff. They use sensors and robotics to fine tune spraying. Another tactic involves selective planting of native plants, especially perennial native grasses. One county was able to eliminate herbicides altogether after a couple of years of plant restoration. Goats are used for certain plants, especially before they bloom. It requires working closely with the goatherd to target use. In addition, Caltrans has begun a multi- year project along Highway 1 in Santa Cruz using weed control mats and a liquid soil sealer.

Title: Target Destruction: Selective Weed Killer Conserves Herbicide and the Environment; Other Roadside Products
Author(s): Scranton Gillette Communications, Incorporated

Date: March 2004
Journal Title: Roads and Bridges, Vol. 42 (3), pp. 63-65
Online:http://trisonline.bts.gov

This article presents a survey of new roadside products, including spot sprayers, which use red and near-infrared beams to detect weeds and activate the spray nozzle. One highway Department user reports cutting herbicide use by 85%. The detection system works best at speeds between 3 and 9 mph, which is still considerably faster than hand spraying. Other products described include a skid-steer rotary mower attachment, a cab-operated boom to place road patches in irregularly shaped spots, outfront mowers and a boom mower that can operate at traffic speeds.

Title: Biological Control of Purple Loosestrife in New Hampshire 1997-2001
Author: Durkis, T.J.
Date: 2003
Report No: FHWA-NH-RD-12323Q (Final Report) ; 59p

Purple loosestrife, Lythrum salicaria, is an invasive, non-native plant introduced in the United States from Europe and Asia beginning in the early nineteenth century. As the purple loosestrife population expanded, concerns increased about its potential impact in moist habitats. Since the 1950s, a variety of mechanical, cultural, and chemical controls have been employed in an attempt to control the effect of the species on natural and manmade wetlands. These methods were either impractical or abandoned due to ineffectiveness or environmental concerns. Biological control of weeds utilizes the introduction of natural enemies to reduce population levels of undesirable plants. Biological control is considered a safe, sustainable, cost effective, long-term method for reducing invasive plant populations. This report summarizes a pilot program instituted by the New Hampshire Department of Agriculture, Markets and Food and the New Hampshire Department of Transportation (NHDOT) to control purple loosestrife in New Hampshire wetlands between 1997 and 2001. The program included the screening, selection and rearing of candidate insects, controlled releases, and monitoring at numerous sites throughout the state. A total of 130,400 *Galerucella* spp. leaf-eating beetles were released during the period. The program was successful in establishing viable populations of these beetles at several locations. The release of beetles adjacent to and within areas proposed for future wetland mitigation creation and along NHDOT right-of-ways established diversity in the introduction of biocontrol of loosestrife over a wider region. It is recommended that biocontrol of this species be maintained and expanded. Community rearing and release is encouraged, and continued monitoring should occur. Further investigations into the possible use of root feeding weevils are recommended.

Title: Weed the Plan when Planning for Weeds
Author: Wanek, M.
Date: 2003
Source: Railway Track and Structures, Vol. 99 (1), pp 24-26

This article describes the vegetation management of Burlington Northern and Santa Fe (BNSF), which oversees 200,000 acres along its 34,000 route miles, which range from subtropical to mountainous environments. It has a system-wide, internally managed program that works in four categories: roadbed, brush, noxious weeds, and crossing acres. The approach is to apply herbicide that works on pre-emergent growth before it becomes a problem. That requires using the appropriate equipment to spray the right chemicals on the proper targets under optimal climatic conditions without interfering with day-to-day operations on the line. Brush and crossing work is done with a combination of mechanical and chemical approaches. The idea is to prevent weeds and trees from resprouting but allowing native grasses and other vegetation that doesn't interfere with operations to revegetate. The roadbed program starts near the first of the year in the warmer climes and gradually moves north as weather permits. Noxious weed program uses contractors who handle different parts of the network based on geographic proximity, with the railroad buying all the herbicides and supplies in bulk for distribution to the contractors as they are needed. As herbicides are repeatedly applied, plants develop a tolerance, but new products take a long time to be developed, which could cause some problems in the future.

Title: NYS Department of Transportation Response to E.O. 13112 Invasive Plant Species
Authors: Falge, J; Frantz, E; Ambuske, R
Date: 2003
Source: International Conference on Ecology and Transportation, Proceedings
http://www.itre.ncsu.edu/cte/icoet

On February 3, 1999, President Clinton signed Executive Order 13112 (E.O.), which calls on state Transportation agencies to work to prevent and control the introduction and spread of invasive species. Nonnative flora and fauna can cause significant changes to ecosystems, upset the ecological balance, and cause economic harm to our nation's Transportation, environmental, agricultural and recreational sectors. For example, introduced plants, such as Phragmites and purple loosestrife, throughout New York State have choked out native plant species and consequently clogged roadway drainage ways and altered environmental habitat. Transportation systems can facilitate the spread of plant and animal species outside their natural range. Those species that are likely to harm the environment, Transportation safety, human health, or economy are of particular concern. The NYS Department of Transportation (NYSDOT) maintains approximately 16,500 miles of highway and annually spends over $9.1 million on vegetation management. Funding for this project is integrated as part of the normal Department operational vegetation management budget. The threat from invasive species increases with human population growth, global trade and disturbance of the environment. Effectively dealing with the problem of invasive plant species presents a significant conservation challenge, both biologically and politically. The prevention of new plant invasions, early detection and monitoring of infestations of invasive plants, and effective control of established invasions through area-wide partnerships have been identified as key objectives in an overall national strategy for invasive plants. Stopping potentially invasive species before they spread from Transportation corridors may be the best option for short-term protection. The Department is implementing a proactive environmental initiative to attempt to eradicate certain existing invasive populations, and control the colonization and spread of species that have demonstrated negative effects to natural systems. Highway corridors provide opportunities for the movement of invasive species through the landscape. Invasive plant or animal species can move on vehicles and in the loads they carry. Invasive plants can be moved from site to site during spraying and mowing operations. Weed seed can be inadvertently introduced into the corridor during construction on equipment and through the use of mulch, imported soil or gravel, and sod. Some invasive plant species might be inadvertently planted in erosion control, landscape, or wildflower projects. Thousands of miles of New York State rights-of-ways traverse public and private lands. Many of these adjacent lands have weed problems and the highway rights-of-way provide corridors for further spread. NYSDOT has an opportunity to address roadside vegetation management issues on both their construction activities and maintenance programs with new levels of cooperation and communication with other state agencies and conservation organizations.

Title: Development and Testing of a Weed Wiper for Roadside Vegetative Control
Authors: Ritter, W.F.; Kemble, L.J.
Date: 2002
Report No: DCT 142,; Final Report; 49p
University of Delaware, Newark
Delaware Center for Transportation
Newark, DE 19716
USA
Delaware Department of Transportation
Bay Road, Route 113, P.O. Box 778
Dover, DE 19903-
USA

The objective of the project was to investigate the potential of using the weed wiper applicator as an alternative method to mowing and broadcast spraying for controlling noxious weeds, brush and plant growth along roadways. An existing weed wiper applicator used for tax ditch herbicide applications was modified by replacing a flat set of applicators which utilized grit abrasive banded to an aluminum channel with radial applicators. The chemicals Roundup, Rodeo, Touchdown and Arsenal were used. They were applied in concentrated and dilute form or as mixtures. Applications of Rodeo, Roundup and Touchdown at the rate of 0.3 gallons per acre were 50% to 75% effective on 1 to 2 year old sweet gum, tulip popular, sumac, cherry and maple with one application. With the addition of 1 part of applicators concentrate Arsenal added to 40 parts of the other chemicals and applied at 0.25 gallon per acre, vegetation control was over 75% with one application. Even vegetation with extensive root systems was controlled and pine, cedar, willow, phragmites, multiflora rose, black locust, holly and sassafras were also controlled in varying degree with one application. The total capital cost for a complete three tank applicator system not including the tractor is estimated to be in the $10,500 range. The cost for roadside utility right-of-way and roadside ditch wood line spraying is in the range of $190 to $200 per mile. This cost includes labor, equipment and chemicals.

Title: Vetch Infestations in Alaska
Author: Nolen, A
Date: September 2002
Report No: FHWA-AK-RD-02-11 ; 39p Alaska Department of Transportation and Public Facilities
3132 Channel Drive, Juneau, AK 99801-7898 USA

Vetch is one of many problematic non-native plants that have become prevalent along Alaska's picturesque highways. Known by the common names tufted vetch, bird vetch and cow vetch; *Vicia cracca* has infested many disturbed areas in south central and interior Alaska. Visual surveys and intensive communication with industry professionals indicate vetch presence in significant amounts in the core area of Mat-Su, Fairbanks and Anchorage with smaller areas present in Seward, Girdwood, Homer, Suton, Soldotna, Delta Junction, Nenana, Denali Park, a few runways along the Kuskakwim River, and sporadically along the Parks Highway. Though infestations are considered a problem, more research in needed to determine the invasiveness of this species before eradication control measures are implemented. Including this species in a general weed management plant is appropriate. Care must be taken not to misidentify other native legumes with similar growth habits as the problem vetch. Many strategies are affective at controlling it but mowing is preferred.

Title: Mapping Ecosystems along Nevada Highways and the Development of Specifications for Vegetation Remediation
Authors: Tueller, P.T.; Post, D.; Noonan, E.
Date: September 2002
Report No: RDT 02-029; 61p
Publisher/Corporate Author(s):
University of Nevada, Reno, Department of Environmental and Resource Sciences
Reno, NV 89502-USA
Nevada Department of Transportation, 1263 South Stewart Street
Carson City, NV 89712,USA

This project inventories the major plant communities and general soil classification units along Nevada highways and recommends the best procedures and management practices for vegetation remediation based on the appropriate ecosystems and soil types. Vegetation and soils were mapped using Landsat thematic mapping data along a five-mile corridor for all Nevada state and federal highways. Soils data were extracted from information provided by the Natural Resources Conservation Service. The maps are presented by county. Revegetation protocols were described for eight general vegetation types associated with Nevada highways. The specifications include site analysis, species selection, site preparation and specific revegetation procedures. The seeding specifications include information on proposed species and species mixtures, fertilization, seeding method, supplemental irrigation and erosion control. Species selected for remediation purposes have been evaluated for drought tolerance, minimum annual rainfall needs, salt and alkali tolerance, seedling vigor, growth habit, suitable soil groups, seeding rates, pure live seed, availability, and general costs for native seed sources. In addition, three specific site examples have been described in detail with specific reclamation steps. Monitoring procedures to evaluate the success of remediation are described. The report also presents an inventory of noxious and invasive weeds and discusses the hazard of possible wildfire along the highways.

Title: War on Weeds
Author: Harper-Lore, B.
Date: 2002
Journal Title: Public Roads, Vol. 66(2), pp. 10-15
Publisher/Corporate Author(s):
Federal Highway Administration
400 7th Street, SW
Washington, DC 20590
USA

Invasive plant species, otherwise known as non-native weeds, can be accidentally or intentionally introduced into a landscape. Invasives can have a devastating impact on native ecosystems, out-competing native plants and crops for space, light, water, and nutrients. In May 2002, to help combat the continent-wide problem of invasive plant species, the Federal Highway Administration sponsored an interagency international conference on invasive plant species. This article discusses the proceedings of the "Weeds Across Borders" conference held in Tucson, Arizona.

Title: In the Weeds : NRVMA Rewards Those Who Can Handle Being Off The Fairway
Author: Zeyher, A.

Date: 2002
Journal Title: Roads and Bridges, Vol.: 40 Issue: 5, pp. 42-45
Publisher/Corporate Author(s):
Scranton Gillette Communications, Incorporated
380 E Northwest Highway, Des Plaines, IL 60016-2282,
USA

This article presents the winners of the 2001 awards from the National Roadside Vegetation Management Association for excellence. They include the city of Duluth, MN, the Florida DOT, Great Bend, KS, and the company of Becker Underwood in Ames, IO. Duluth roadsides include 40 acres of gardens along the Lake Superior shore, which are maintained with a minimum of chemicals. Florida has incorporated highway beautification into all its highway construction plans at the earliest design stages and funds beautification in proportion to construction. The noxious weed Department of Barton County, home to Great Bend, has learned to rely on native grasses to reduce the need for mowing and deprive the four most invasive strangers of growing space. Becker Underwood's color sprays let vegetation managers see where applications have been made. They break down in light and water.

Title: Research Pays Off: Biological Control of Purple Loosestrife: Wetlands Weed Meets the Beetles
Author: Cygan, D.
Journal Title: TR News, Issue 213, pp. 52-53
Publisher/Corporate Author(s):
Transportation Research Board, 2101 Constitution Avenue, NW
Washington, DC 20418, USA

Purple loosestrife (*Lythrum salicaria*) is a noxious weed species that has become a common problem throughout North America. With increased sensitivity to the management of this invasive plant, the New Hampshire Department of Transportation's Bureau of Environment, in conjunction with the New Hampshire Department of Agriculture's Market and Foods Division, has created a purple loosestrife biological control program that uses two host-specific plant feeding insects. Further details are presented in this article.

Title: Roadside Vegetation Managers Keep Track with GIS/GPS
Date: 2001
Journal Title: Public Works, Vol. 132 Issue: 1, pp 56-58
Publisher/Corporate Author(s):
Public Works Journal Corporation;
200 South Broad Street, Ridgewood, NJ 07451, USA

Roadside vegetation managers are finding that using GIS/GPS-based maps to monitor heir programs can cut weed control costs by increasing the effectiveness of weed treatments and reducing waste and payouts for liability claims alleging misapplication of herbicides. The GIS/GPS maps' accuracy to within a few feet reduce liability claims because they more clearly document where herbicides have been used and enable more precise application of herbicides. By informing nearby landowners of weed infestations y mailing out GIS/GPS-based maps, managers saw an increase in the number of landowners practicing weed control on their parcels. The maps also help managers to better tailor budgets and explain them to policymakers and elected officials.

Title: GPS Helps Manage Roadside Vegetation
Author: Marum, E.
Date: 2000
Journal Title: Roads and Bridges, Vol. 38 Issue 5, pp. 36-38
Publisher/Corporate Author(s):
Scranton Gillette Communications, Incorporated
380 E Northwest Highway, Des Plaines, IL 60016-2282, USA

The Integrated Roadside Vegetation Management (IRVM) is Iowa's long-term approach to reintroduce native grasses and wildflowers to roadsides creating beautiful passages capable of resisting weeds and soil erosion while using little or no maintenance. A few years ago, Clinton County, Iowa, put a three-product chemical injection system on their spray truck to save time and money. Road crews went from treating 20 mi of roadway to 50 mi each day, and in nearly every case they were doing a better job. The next breakthrough came when the deputy director of the county conservation board was tipped off to a new Roadway Management System that records the placement of multiple herbicides to an onboard computer connected to a differentially corrected global positioning system (GPS) receiver. With a system like this, the county could integrate data from years of mapping and spray areas where weeds proliferated. At the same time, crews could carefully avoid sensitive areas they had nurtured over the past decade. A few seasons of use, good empirical data logging of what goes where, and careful management of that data and visual confirmation will let Clinton County know for certain. However, if it works, Iowa will benefit with more beautiful roadsides managed more effectively by the same number of people using less intrusive methods of management. A sidebar provides details on the Mid-Tech's Roadway Management System.

Title: Assessment of Exotic and Invasive Plants along Roadways in Tennessee (Final report)
Authors: Lambdin, P.L.;Grant, J. F.
Date: August 2000
Publication: Report No.: TNRE-S110, 170p
Tennessee Univ., Knoxville. Agriculture Experiment Station

A comprehensive two-year study focused on identifying and assessing incidence, distributions, and impact of exotic and invasive plant species along interstate right-of-ways in Tennessee. Goals of this study were to: (1) identify exotic and invasive plant species established along interstates, (2) develop a species listing of the floral composition along interstates, (3) assess the potential threat of exotic and invasive plant species becoming an economical and environmental pest along highways, and (4) evaluate the potential opportunities for biological control of these exotic and invasive plants, reducing biological diversity, reducing agricultural productivity, increasing costs of agricultural production, and increasing costs of managing land areas. During this study, 538 plant species, representing 19.8% of the 2,715 plants found, 32.7% (n=176) were exotic species-thus, about 1 of every 3 plant species found along the interstate was an exotic species. More than 75% of the plants on the TN State Noxious Weed Seed List, and more than 60% of those listed by TN-EPPC, were found. These data suggest that the interstate system may serve as a corridor for the movement and establishment of exotic plant species. Improved weed management strategies can now be implemented to reduce the spread of problematic exotic and invasive plant from interstates to agricultural, natural, forest, and urban habitat. Incorporation of well designed biological control strategies into weed management efforts provide an environmentally friendly, cost efficient, and sustainable method of reducing certain exotic plant species. This study provides the first intensive, state-wide, interstate assessment of exotic and invasive plant conducted in the U.S. and provides a solid foundation for future management efforts against these plant pests.

Title: Assessment of Exotic and Invasive Plants Along Roadways in Tennessee: Potential for Biological Control
Authors: Lambdin, P.L.; Grant, J.F.
Date: 1999
Report No: RES1101,; Final Report; 162p
Publisher/Corporate Author(s):
University of Tennessee, Knoxville, Agricultural Experiment Station
Knoxville, TN 37901-1071 USA
Tennessee Department of Transportation, James K. Polk Building, Fifth and Deaderick Street
Nashville, TN 37243-034 USA
Federal Highway Administration, 400 7th Street, SW
Washington, DC 20590 USA

A comprehensive two-year study focused on identifying and assessing the incidence, distribution, and impact of exotic and invasive plant species along interstate right-of-ways in Tennessee. Goals of this study were to: 1) identify exotic and invasive plant species established along interstates; 2) develop a species listing of the floral composition along interstates; 3) assess the potential threat of exotic and invasive plant species becoming an economical and environmental pest along highways; and 4) evaluate the potential opportunities for biological control of these exotic and invasive plants. Exotic and invasive plant species can degrade the natural composition of areas impacting native plants, reducing biological diversity, reducing agricultural productivity, increasing costs of agricultural production, and increasing costs of managing land areas. During this study, 538 plant species, representing 19.8% of the 2,715 plant species documented in Tennessee, were found at qualitative and quantitative sampling sites along interstates. Of 538 plants found, 32.7% (n=176) were exotic species - thus, about 1 of every 3 plant species found along the interstate was an exotic species. More than 75% of the plants on the Tennessee State Noxious Weed Seed List, and more than 60% of those listed by the Tennessee Exotic Pest Plant Council, were found. These data suggest that the interstate system may serve as a corridor for the movement and establishment of exotic plant species. Improved weed management strategies can now be implemented to reduce the spread of problematic exotic and invasive plants from interstates to agricultural, natural, forest, and urban habitats. Incorporation of well designed biological control strategies into weed management efforts provide an environmentally friendly, cost efficient, and sustainable method of reducing certain exotic plant species. This study provides the first intensive, state-wide, interstate assessment of exotic and invasive

Title: Precision Offset Spray System for Roadway Shoulder Weed Control
Authors: Slaughter, D.C.; Giles, D.K.; Tauzer, C.
Date: 1999
Journal Title: Journal of Transportation Engineering, Vol. 125 Issue: 4, pp. 364-371
Publisher/Corporate Author(s):
American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, VA 20191-4400
USA

A precision offset spray system was developed for use by highway maintenance Departments for the control of unwanted vegetation in the graded shoulder area adjacent to roadways. The offset sprayer consisted of two fundamental elements: a machine vision system and a rapid response intermittent spray system. This study showed that it is feasible to use machine vision on a moving vehicle to automatically detect the presence of green plant material and to apply herbicides exclusively to plants and not to nonplant materials, such as bare soil. The system substantially reduced the amount of herbicide applied to nonplant material. In system tests, there was up to a 97% reduction in applied spray mix over conventional continuous spray applications with a plant deposition rate of 57% of continuous spray systems. Implementation of this technology would allow highway maintenance Departments to reduce the cost of weed control and the amount of chemical herbicides released into the environment, while maintaining current levels of weed control efficacy.

Title: Herbicides Help Illinois DOT Control Roadside Weeds
Author: Caylor, P.
Date: 1998
Journal Title: American City and County, Vol. 113 Issue: 3, pp. 17-18
Publisher/Corporate Author(s):
Intertec Publishing Corporation
6151 Powers Ferry Road, NW, Atlanta, GA 30339-2941, USA

Mowing is the standard method for eliminating weeds and woody brush from highway roadsides. The Illinois Department of Transportation (IDOT), however, has found herbicides to be a more effective solution. In 1997, IDOT began using Garlon 3A to take care of weeds and brush such as Canada thistle, musk thistle, teasel, willow, box elder, elm, and black locust, without disturbing sensitive ornamentals. Garlon 3A is not "soil active," meaning it does not seep into the soil, so the ornamentals do not absorb it. In areas without ornamentals, IDOT uses Tordon 101M. Spraying herbicides costs about $15 per acre, while mowing costs approximately $30 per acre. Moreover, the results have been better because herbicides are designed to be absorbed by the plant, thus killing it. Spraying is also safer for IDOT workers, since it does not have to be repeated like mowing and therefore reduces workers exposure to high-volume, high-speed traffic.

Title: Weeds Zapped with Laser Accuracy
Date: 1996
Journal Title: Roads and Bridges, Vol. 34 Issue: 5, p.50
Publisher/Corporate Author(s):
Scranton Gillette Communications, Incorporated
380 E Northwest Highway, Des Plaines, IL 60016-2282, USA

In California, an age old endeavor of killing weeds is meeting up with a new technology. CALTRANS has a stated goal of reducing pesticide use by 50% by the year 2000. This year experiments are being done with an innovative agrichemical sprayer that can sense the presence of weeds and then zap them with laser-like precision. The PhD6000 sprayer comes with its own light source, detector and computer circuitry and can detect when chlorophyll is present. The circuitry then triggers a burst of herbicide. The new sprayer has the potential to save time, money and effort for the crews responsible for roadside maintenance.

Title: New Treatment Combinations for Control of Brush and Vegetation Management Along Indiana Roadsides. Final Report
Author: Morre, D.J.
Date: November 1995
Report No: FHWA/IN/JHRP-95/3; Proj No. C-36-48M; 122p
Publisher/Corporate Author(s):
Purdue University/Indiana Dept of Transp. JHRP; School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA
Indiana Department of Transportation
100 North Senate Avenue, Indianapolis, IN 46204 USA
Federal Highway Administration
400 7th Street, SW, Washington, DC 20590 USA

This report presents the results from a research project to develop and implement new treatment mixtures for control of problem brush, trees and other woody species and herbicide-resistant weeds along Indiana roadsides. An environmentally safe mixture of *trichlopyr* (Garlon Herbicide) and ammonium nitrate for one application control of deciduous roadside vegetation was developed. Also discovered and developed was a new, environmentally safe and effective TR series of additives that enhance the action of the auxin herbicides (*trichlopyr*, 2,4-D, *picloram*) for inclusion in both the brush control mixture and for possible use for the control of milkweed, canada thistle, bindweed, ground cherry and other perennial, herbicide-resistant roadside weeds.

Title: Prevalence of weeds along Pennsylvania roadways: Results from a ten-county survey.
Author: Clark, B. J; Curran, W. S. and M. W. Myers.
Year: 2002
Source: Proc. NEWS 56:99.
Website: http://www.cas.psu.edu/docs/CASDEPT/AGRONOMY/weeds/roadside.html

Roadways in the state of Pennsylvania continue to be a vector for the transmission of weeds along their corridors to either natural settings or agricultural land. As the concern increases to stop the potential spread of invasive and troublesome weeds, roadsides are continually becoming more and more of a focus as a method by which weeds expand their distribution. This survey was conducted to assess the frequency and severity of weeds along secondary roadways in Pennsylvania.

Title: Roadside Vegetation Management Research Report. Thirteenth Year Report (Rept. for 23 Mar 98-22 Mar 99)
Authors: Gover, A. ; Johnson, J. M. ; Kuhns, L. J.
Date: January 2000
Publication: Report No.: PA-462099-01, 64p ;
Pennsylvania State Univ., University Park. Coll. of Agriculture Sciences

The thirteenth year report on a cooperative research project between the Pennsylvania Department of Transportation, Bureau of Maintenance and Operations; and the Pennsylvania State University, College of Agricultural Sciences; including: Brush control research evaluating basal bark and low volume foliar herbicide applications; Evaluation of Giant knotweed control and conversion into low maintenance grasses; Herbaceous weed control research evaluating the effect of herbicides on the control of Canada thistle and tolerance of fine fescues; Comparison of seeding methods for the establishment of Formula L; Comparing various herbicides and methods of vegetation control for use under guiderails; Evaluating the use of herbicides for the establishment of native grasses; Review of demonstrations evaluating backpack-based applications, controlling Ailanthus using low volume backpack applications, and converting an Ailanthus infestation into fine fescues.

Title: Roadside Vegetation Management at the Pennsylvania State University
Source: http://rvm.cas.psu.edu/intropage.html

The Pennsylvania Roadside Research Project was initiated in 1985 to assist the Pennsylvania Department of Transportation's Bureau of Maintenance and Operations in the ongoing development of its roadside vegetation management program. The original focus was on the evaluation of materials and methods for selective brush control, Canada thistle management in crownvetch, and growth regulation of roadside tall fescue turf; and to serve as an unbiased information source for the evaluation of emerging vegetation management technologies. The Project focus has expanded to include all aspects of roadside vegetation management, using the Integrated Vegetation Management approach. The aim is to preserve as much desirable vegetation as possible while minimizing undesirable vegetation and maintaining a desirable aesthetic, within the confines of finite resources.

Title: Roadside Vegetation Management: Suggested Herbicide Mixtures for Roadside Vegetation Management
Author: Department of Horticulture College of Agricultural Sciences
Date: 2000
Website: http://rvm.cas.psu.edu/Publications/Herbicide_Suggestions.pdf

This publication provides examples of herbicide mixtures for different vegetation concerns along roadsides. It is intended to be illustrative, not exhaustive. Listed rates represent one point in a possible range of rates. The product label is the authoritative document on the use of a product.

Title: Roadside Vegetation Management Research Report - Seventeenth Year Report
Author: The Pennsylvania State University - Research Project # 85-08; Report # Pa 03-4620 + 85-08
Year: 2002
Website: http://rvm.cas.psu.edu/2003/2003PDF/AR03_cover-pv.pdf

In October, 1985, personnel at The Pennsylvania State University began a cooperative research project with the Pennsylvania Department of Transportation to investigate several aspects of roadside vegetation management. An annual report has been submitted each year which describes the research activities and presents the data. The previous reports are here listed.

Many of the individual reports in this document make use of statistics, particularly techniques involved in the analysis of variance. The use of these techniques allows for the establishment of criteria for significance, or, when the differences between numbers are most likely due to the different treatments, rather than due to chance. We have relied almost exclusively on the commonly used probability level of 0.05. When a treatment effect is significant at the 0.05 level, this indicates that there is only a five percent chance that the differences are due to chance alone. At the bottom of the results tables where analysis of variance has been employed, there is a value for least significant difference (LSD). When analysis of variance indicates that the probability that that variation in the data is due to chance is equal or less than 0.05, Fisher's LSD means separation test is used. When the difference between two treatment means is equal or greater than the LSD value, these two values are significantly different. When the probability that the variation in the data is due to chance is greater than 0.05, the L.S.D value is reported as 'n.s.', indicating non-significant. This report includes information from studies relating to roadside brush control, herbaceous weed control, roadside vegetation management demonstrations, and total vegetation control under guiderails. Herbicides are referred to as product names for ease of reading. The herbicides used are listed on the following page by product name, active ingredients, formulation, and manufacturer.

Title: PENNDOT Manages Roadsides Via Computer
Author: Nelson, C.D.
Year: 1996
Journal: Better Roads, Vol. 66 Issue 10, pp. 21-22

The typical roadside vegetation management program involves setting up contracts, and purchasing materials and equipment. These needs are limited by a fiscal budget. Computer programs can help management offices prepare budgets, prepare vegetation management plans, accurately record applications, track production in acres, hours, and costs, and lets roadside management and supervisors see where their agency needs improvement and additional funds.

Title: ROADVEG: Utah Department of Transportation Roadside Vegetation inventory and geographic information system
Authors: Bickford, Ira; Curto, Michael; Glazier, Chris; MacMahon, James A.
Source: Transportation Research Record Num.1650, Nov 1998. pp. 13-18

The Utah Department of Transportation (UDOT), in collaboration with the Utah State University Ecology Center, has created a geographic information system (GIS) of spatially referenced roadside and context landscape attributes pertinent to roadside vegetation management. Construction of the ROADVEG GIS involved the design of a relational database, the assignment of attributes to 2200 km (1,365 mi) of road segments through on-the-road field inventories, and the linkage of database attributes to spatial coverages for GIS presentation and query. The ROADVEG GIS offers UDOT personnel a new way to remotely assess existing roadside and context vegetation attributes along Utah's roadways, as well as a potentially powerful method of performing multivariate spatial queries for long-range planning. Through queries of the ROADVEG inventory, road segments with specified multivariate conditions are readily identifiable. Visual depictions of multiple vegetation management scenarios with varying cost-benefit ratios are now possible. (Author abstract) 24 Refs.

Title: Spatial analysis of herbicide decay rates in Louisiana
Authors: Obenshain, K.R.; Metcalf, M.C.; Abdelghani, A.A.; Regens, J.L.; Hodges, D.G.; Swalm, Ch.M.
Source: Environmental Monitoring and Assessment, Vol. 48 Num. 3, Dec 1997. pp. 307-316
Corporate Source: Tulane Univ Medical Cent, New Orleans, LA, USA

This analysis presents results based on a five-year study recently supported by the Louisiana Department of Transportation and Development (DOTD) in which the acute toxicity, fate and effect of herbicide mixtures on human health and the environment were assessed. Three sites were routinely sprayed by DOTD to kill weeds along the roadsides. Two herbicide mixtures were used, 2,4-D and Roundup, and Garlon 3A and Roundup. Water, vegetation, soil and sediment samples were collected quarterly for three years and were analyzed for pesticide content to study the fate and impact of herbicides in the environment. Results indicate a correlation between soil type, herbicide type, and persistence of the herbicide in the environment. Using the correlations found in these data, spatial analysis identified areas where herbicide use may potentially cause surface water and sediment contamination, based on soil composition/properties, type of herbicide applied, and proximity of water bodies to sprayed areas.

Title: County turns to Herbicides to Save Money
Author: Chesler, A.
Date: 1997
Source: Public Works, 128: 76-77

Two years ago Walton County, Georgia, began a program to gradually convert its mechanical mowing approach to the use of professionally applied herbicides to control roadside vegetation. The county sprays about 150 miles of roadway three times a year at a substantially reduced cost, then mows once in the fall. The goal is to increase the area being sprayed by about 50 miles a year until all county roadsides are maintained by spray. (Edited author abstract)

Title: How South Carolina Cut Roadside Maintenance Costs
Author: Aitken, James B.
Source: Better Roads Vol. 65 Num. 2, Feb 1995. pp. 30-31
Corporate Source: Clemson University's Sandhill Research and Education Center, Columbia, SC, USA

Four years ago, the South Carolina Department of Transportation initiated the restructuring of a fragmented herbicide program. Currently, the program is already being implemented. By implementing the program, labor and costs have been cut, herbicide use has been simplified, and the highways have been made safer for the driving public.

Title: Managing Roadside Vegetation in Alaska. Final Report
Author: Johnson, L.A.
Year: 1995
Corporate Source: Alaska University, Fairbanks, Institute of Northern Engineering , Fairbanks, AK, 99775, Alaska Department of Transp and Public Facilities, Engineering and Operations Standards, 3132 Channel Drive, Juneau, AK, 99801-7898, Federal Highway Administration, 400 7th Street, SW, Washington, DC , 20590,
Report Number: SPR-UAF-92-11; INE/TRC 94. 27p

This report examines the problem of controlling undesirable roadside vegetation, primarily tall wood shrubs and trees, in the central and northern Districts of Alaska. Other vegetation management concerns, such as reestablishing vegetation on disturbed areas following road construction and maintaining desirable, low growing species along roadsides are briefly addressed. This report does not directly examine vegetation problems in the much wetter, maritime climate of Southeast Alaska. Roadside vegetation control is a costly, recurring problem for the Alaska Department of Transportation and Public Facilities (AKDOT&PF). Mechanical cutting is the dominant means of control presently, although herbicides were widely used in the past, and these have had some recent but limited use in Southeast Alaska. To reduce most effectively the extent of undesirable woody species along the roadside, it is preferable to use multiple methods, such as mechanical cutting in conjunction with a limited basal spray (herbicide) program or with hand weeding. Such an integrated vegetation management (IVM) approach will help reduce both the number of species as well as the number of individual woody plants that might persist. On the basis of this project, it is recommended that AKDOT&PF develop a long term IVM program that includes vegetation monitoring and a maintenance program to enhance desirable vegetation along roadsides.

Title: Roadside Vegetation Management: Herbicides and Beyond
Author: Sherman, F.
Year: 1995
Journal: Transportation Builder Vol: 7 Issue 4, pp 18-20

Chemical treatment of roadside vegetation can be an effective, but unpopular choice in vegetation management. This article describes various approaches to roadside vegetation control that go beyond herbicides. Mowing and planting are favored by the public, and occasionally, herbicides and growth retardants can be used in spot spraying. Budget constraints can dictate the amount of work that can be done overall; consequently, a prevention approach, such as plantings that require minimal attention, may be an appropriate solution. The integration of spraying, manual labor, and prevention can culminate in a practical plan for weed control.

Title: Texas DOT tests geotextiles for roadside weed control. (Texas Depart. of Transportation) (Grounds & Roadside Maintenance)
Year: March 1997
Source: American City & County, Vol. 112, Num. 3, pp.16

Tall weeds growing under guardrails present a fire hazard, are unsightly, and cut off vision. An area near Austin, TX was deemed too dangerous for a worker with a hand-held weeder. Therefore the DOT is working with Texas A&M Univ to test geotextiles matting at the site to determine feasibility.

Title: County's roadside vegetation management program is a winner.
Year: March 1995
Source: Public Works, Vol.126, Num. 3, pp. 58

Umatilla County, OR's Weed Control program, which was established during the 1950s, covers roadside vegetation management and weed control. Its 1994-1995 budget has been set at $340,000, of which $209,000 is intended for roadside vegetation management. The program aims to provide the public with a safe and pleasureable driving environment. Its success relies on open communications, personal integrity and a cooperative attitude. It received the National Roadside Vegetation Management Assn. Award for Roadside Excellence in the County Category on Oct. 13, 1994.

Title: Managing the Roadside
Year: 1996
Journal: Texas Transportation Researcher Vol: 32, Issue Number 3, pp. 9
Corporate Source: Texas Transportation Institute, Texas A&M University, College Station, TX, 77843-3135

Roadside vegetation plays an important role in the roadside ecosystem. Plants stabilize soils against erosion and provide a visible boundary at the pavement edge. But too much of a good thing can create havoc. When plants and insects threaten the traveling public, measures must be taken to control the vegetation. Texas DOT uses maintenance measures designed to encourage the growth of good plant species thereby reducing the need for excessive spraying of chemicals and overall reducing the total cost of roadside maintenance. By continuing to explore treatment methods which are environmentally sound and promoting the growth of native species, Texas DOT will assure responsible, safe and fiscally sound maintenance practices.

Title: Control of musk thistle (*Carduus nutans*) with Transline® and Escort® along roadsides
Authors: Meyer, Robert E; Simpkins, Cynthia L.; McCully, WayneG; and Steven G. Evans
Date: March 1994
Source: Texas Transportation Institute

In this study, the herbicides Escort® (metsulfuren methyl) and Transline® (clopyralid) were evaluated for their effectiveness in the treatment of roadsides infested with musk thistle. Treatment areas consisted of three separate plots, which were sprayed once between February and April 1992. The treated plots were assessed at one, two and three months following spraying. It was found that Transline caused yellowing and curling of leaves and stems one month following treatment. At two months post treatment, almost all thistles were killed. The dosage of Transline used for the three areas was: 389, 779, and 1029 ml/ha. It was also found that the herbicide effectively prevented further musk thistle invasions in subsequent years. Escort® was used on three additional plots at dosages of 35.0, 52.5, and 70.0 g/ha. This product effectively killed nearly all thistles on the plots at two months following treatment. However, after three months, small thistles appeared at all locations. Further, it was observed with the use of both of these herbicides that many native plants, such as prairie coneflower, were eradicated from the sites.

Title: Progress report on Research to identify effective foliar spray and mechanized spray delivery systems for the selective control of mesquite on rights-of-way
Authors: Ueckert, Darrell N.; and Allan W. McGinty
Date: March 1998
Source: Texas Department of Transportation

The study tested high volume foliar sprays with a mixture of 0.5% clopyralid and 0.5% triclopyr ester surfactants. Delivery methods included: a "Brush robot", which was equipped with spot guns that sprayed plants with 120 kPa of herbicide as the machine's sensors detected a weed; "mesquite-sensing booms" sensed plants using horizontal beams of modified light, and dispersed herbicides through automated rollers (made of PVC pipe and carpet) attached to a tractor; a weed sprayer attached to an ATV, which was used as the operator detected mesquite plants. Success rates for these methods averaged 93%, and regression analysis of associated operating costs were included.

Title: Colorado DOT mowing guidelines.
Year: July 1998
Source: Public Works, Vol. 129, Num. 8, pp. 26

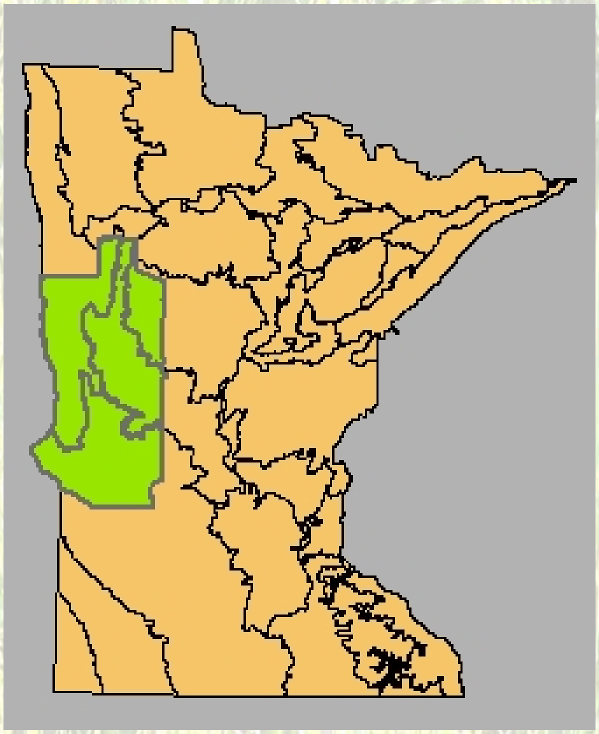
Guidelines in roadside mowing include the use of appropriate mowers and brush cutters and the correct application of mowing methods such as full width mowing, swath mowing and spot mowing. Several goals such as establishing and maintaining clear vision areas, providing vegetation an intermediate height, preserving native vegetation, providing habitat for wildlife and controlling noxious weeds should be met. Safety measures in roadside mowing operations should also be observed.

Title: Roadside Vegetation Management: Final Guidelines Document For Colorado DOT
Authors: Kohlhepp, P.F.; Sanders, T.G.; Tackett, C.C.; Walters, R.W.
Date: 1995
Report No: CDOT-R-CSU-96-5; Study No. 230.03; 143p
Publisher/Corporate Author(s):
Colorado State University, Fort Collins; Department of Civil Engineering, Fort Collins, CO 80523, USA
Colorado Department of Transportation; 4201 East Arkansas Avenue Denver, CO 80222, USA
Federal Highway Administration; 400 7th Street, SW, Washington, DC 20590 USA

The purpose of this document is to outline roadside vegetation management practices recommended in Colorado. It is expected that the text of this document will replace the current chapter on Roadside Appearance in the Colorado Department of Transportation Maintenance Manual. The document is organized in the following twelve chapters: (I) Introduction; (II) Federal and State Regulations; (III) Methods of Vegetation Management; (IV) Determining Levels of Vegetation Management; (V) Mechanical Operations; (VI) Chemical Operations; (VII) Environmental and Safety Considerations; (VIII) Control of Noxious Weeds; (IX) Trees and Brush; (X) Wildlife Habitats and Wetlands; (XI) References; and (XII) Additional Relevant Documents. There are four appendices: (A) Federal and State Contacts; (B) Phenology, Occurrence and Control of State-Designated Weeds; (C) Background of County Designated Undesirable Plants; and (D) Glossary.

Appendix B. User Guide for GPS/GIS Roadside Weed Management Systems

User Guide for GPS/GIS Roadside Weed Management Systems



October 2007

Mn/DOT District 4

Management Practices for Weed Control in Roadway Ditches and Rights-of-way

Submitted to Minnesota Department of Transportation

Minnesota Department of Transportation

UNIVERSITY OF MINNESOTA

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October 2007

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Shannon Wait, Mn/DOT District 4 Maintenance, Transportation Generalist, Alexandria
Barb Loida, Mn/DOT Program Development Engineer, Research Services Section, served as Administrative Liaison
Shirlee Sherkow, Mn/DOT Marketing/Research Librarian, Research Services Section, served as Administrative Liaison

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Introduction

Management of weed infestations along highways' rights-of-way is crucial for driver safety, pavement maintenance, and storm water management. This is usually a costly undertaking, demanding substantial financial, personnel, and equipment allocations. Agencies charged with this responsibility contend with numerous challenges, many emerging following selection of type of control measures to be applied. Further, conflicts often arise due to the diversity of the goals of various agencies concerned with management of natural resources, the environment, and others. For instance, management of vegetation when driven by the desire for maintenance of clean, groomed roadside environments is often in conflict with the desire for preservation of diverse plant communities. Control measures approved for use under given situations may be in contradiction to another agency's regulations. For example, herbicides allowed by the Federal Highway Administration may not meet approval of a U.S. Forest Service official for use in areas where noxious weed infestations extend outside of road easements. Cost reduction considerations are often in opposition to environmental concerns. Interest in biodiversity preservation is contrary to the need to create the often preferred mono-species environment.

A common problem encountered by weed managers is obtaining accurate information on location of problem weeds over the vast natural landscapes. In theory, this can be accomplished through conducting regular inventories in the subject ecosystems. Where infestations over given landscapes are uniform, homogeneous and contiguous, conducting required inventories may be feasible. However, in the normally large natural landscapes, infestations are rarely uniform and/or homogenous in nature. Conducting inventories over such areas would be impractical, or where attempted, will be costly and demand considerable resources. Obtaining this information may be possible through use of alternative approaches. Two commonly used approaches are: (1) sampling (surveying) smaller areas and using obtained information to extrapolate or predict infestations over large areas, or (2) use of models to predict occurrence or potential for invasion of a given area by target weed species.

Figure 1. Canada thistle plant.

This User Guide describes procedures adopted in conducting surveys aided by GPS, processing and analyzing the recorded data, and application of data in evaluating infestations and effects of treatments in Mn/DOT's District 4. The objectives of this project, initiated in

June of 2004, were: (1) perform a literature review of publications related to the project (2) evaluate the procedures developed by Mn/DOT District 4 for surveying and mapping the population of noxious weeds along highways (3) create a method for predicting the population dynamics of noxious weeds, and (4) develop a user guide for the Global Positioning Systems (GPS) and Geographic Information Systems (GIS) component of the project.

Chapters 1 and 2 describe the field survey and data collection as conducted in this work; chapters 3 and 4 review procedures followed in processing and analysis of data, while the last two chapters (5 and 6) discuss the application of obtained results in weed management.

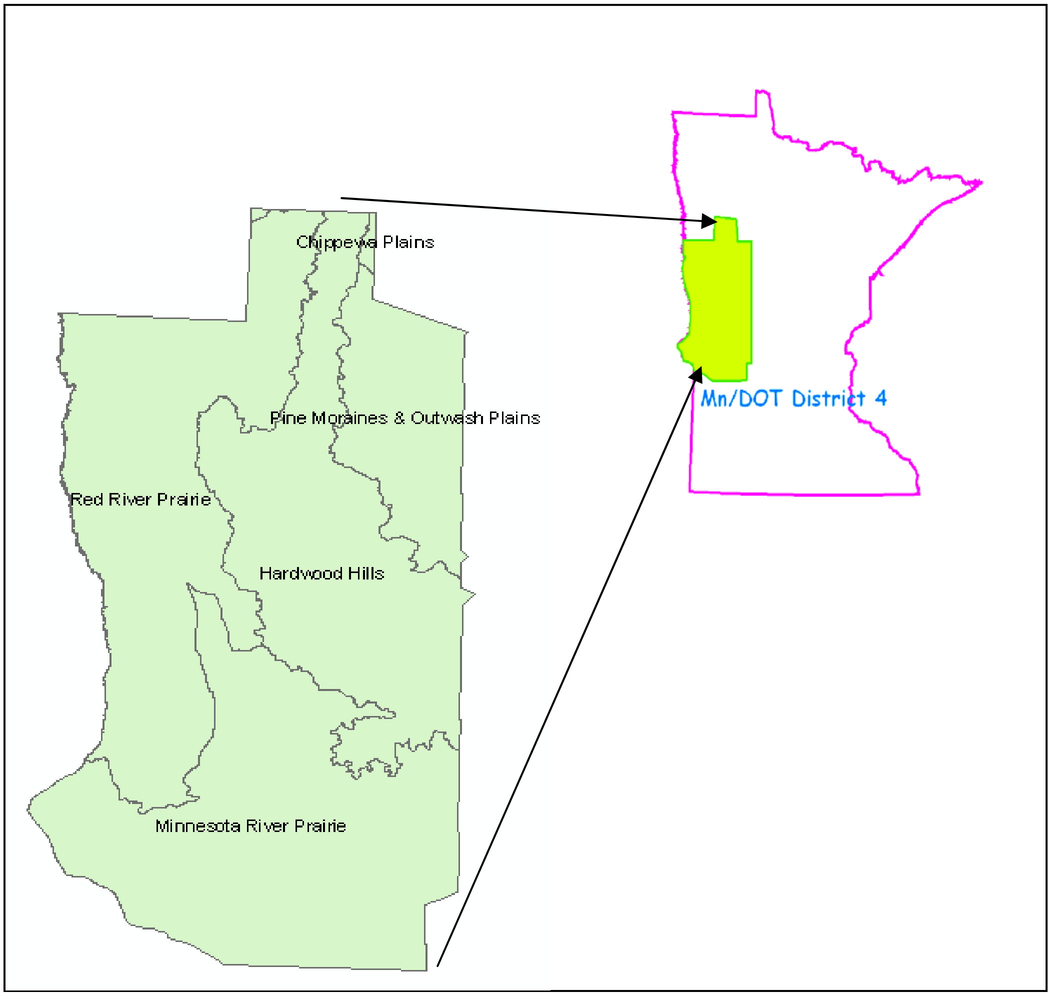


Figure 2. Location and ecological zone boundaries of Mn/DOT's District 4 in Minnesota.

Chapter 1

Preparations for Field Surveys

Purpose: This section of the User Guide offers a summary of pre-survey activities. Brief descriptions covering sample selection procedures, GPS equipment used in the data recording, as well necessary data dictionary, are provided.

1.1 Selection of samples - ¼-mile segments

In 2000 Mn/DOT District 4 initiated the sampling surveys for the three problem weed species. The survey adopted use of the 7, 3-mile sampling sites, which were selected and have since been used in ongoing surveys.

The current project has adopted use of this design and one other comprising of a larger number of ¼-mile long segments. During the surveys conducted in 2004, a sample of 100, ¼-mile segments were selected through random selection from pooled population of all ¼-mile mile marker positions in District 4. This method of sample selection was different from the stratified sample selection method used in selection of samples adopted in the 2005 surveys. Selection of the samples used in 2005 survey involved the following steps (details in chapter 6):

All mile posts for the highways in District 4 under Mn/DOT management are first presented in a table, (table 1.1). A required sample size, in this case 100 ¼-mile segments, is selected, following stratified random sampling. This will ensure proportional representation of sampling sites across ecological zones. The sample (100 ¼-mi. segments) is selected following stratified random sampling design. This is performed by first determining the total linear miles of highways under Mn/DOT management in each ecological zone, and for the entire study area (Mn/DOT District 4). The number of sampling sites to be selected for an ecological region, N_{EZ}, is determined as:

$$N_{EZ} = 100 * \left(\frac{Miles_{EZ}}{Miles_{D4}} \right)$$

where $Miles_{EZ}$ = total linear[1] miles (see definitions in Appendix B of this Guide) of Mn/DOT roads in the ecological zone

$Miles_{D4}$ = is total linear mile in the entire study are (District 4).

The appropriate sample number for an ecological zone is selected using MS EXCEL® randomizing tools on the population of reference posts (or ¼-mi segmID units, table 1.1) for

[1] Linear mile in the scope of this project, is defined as the total road miles, driving in one direction, of the unpaved areas (roadsides and median, where available) from fenceline-to-fenceline of highway right-of-way.

each ecological zone. This is repeated for all ecological zones, with the sum number of selected sites totaling 100.

Table 1.1 Sample population of reference posts in the Mn/DOT managed highways in District 4.

Ecological Zone	**GIS_ROUTE**	**REF_POST (¼-mi intervals)**	**¼-mi SegmID**
Red River Prairie	I94	1.00	I94_1.00
Red River Prairie	I94	1.25	I94_1.25
etc..	….	….	….
Minnesota River Prairie	MN104	13.25	MN104_13.25
Minnesota River Prairie	MN104	13.50	MN104_13.50
Minnesota River Prairie	MN104	13.75	MN104_13.75
Minnesota River Prairie	MN104	14.00	MN104_14.00
etc..	….	….	….
Pine Moraines & Outwash Plains	MN113	1.55	MN113_1.55
Pine Moraines & Outwash Plains	MN113	1.80	MN113_1.80
Pine Moraines & Outwash Plains	MN113	2.05	MN113_2.05
etc..	….	….	….

These procedures were adopted in selection of survey samples (Table 1.2) adopted in the surveys conducted in 2005

Table 1.2 Sampling sites selected in ecological zones in District 4 for 2005 surveys.

Ecological Zone	**No. Sampling Sites**
Chippewa Plains	1
Hardwood Hills	22
Minnesota River Prairie	41
Pine Moraines & Outwash Plain	6
Red River Prairie	33
Total District 4	**103**

1.2 Data collection / recording protocols

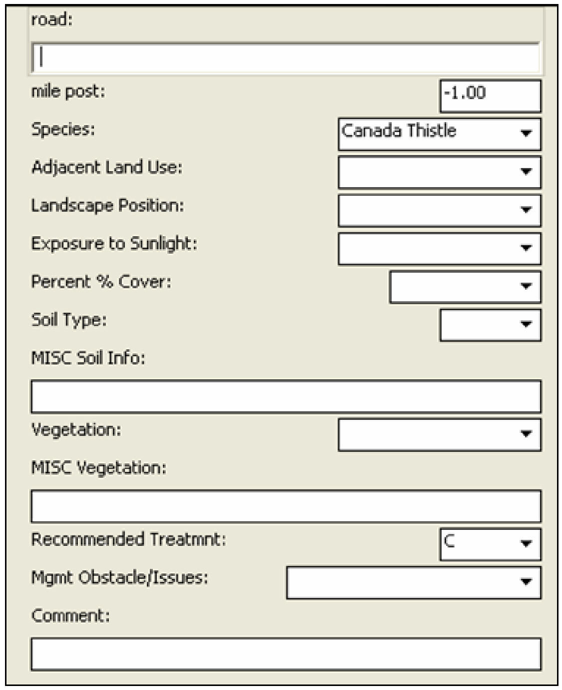
To facilitate ease in data collection and recording, a data dictionary (Table 1 and Figure 3) was created using GPS Pathfinder Software tools. The Mn/DOT District 4 initiated construction of the data dictionary for application in surveys initiated in 2000. The parameters considered important to record data on, and included in the dictionary, are listed in Table 1.3. The dictionary avails forms or templates with space for data entry, either as "line entry" or by "pull-down" menus selections. Data on infestations is recorded by either inputting the information through the keyboard at provided spaces, or by selecting from a list in a pull-down menu (see Figure 1.1). Entries follow the order as provided for in the data dictionary, beginning with type of map to be created (Spot, Polygon or line), Roadway information, Mile Post, etc. The data recording order is as per the sequence in the data dictionary (Table 1.3), with the first item in the list being recorded first on to the last item in the dictionary (comments).

The surveys and data collection and recording were conducted in all the unpaved section, fence-line-to-fence-line in the rights-of-way (Figure 1.2) of all highways managed by Mn/DOT's District 4.

Instructions on use of the Trimble® Pro XR GPS units are as presented in Appendix E

Table 1.3 Attributes and options in the GPS data dictionary for which data was recorded during field surveys.

S/No.	**Attribute**	**Options**	**Entry Method**
1	Plot or Spot	Indicates Plot or Spot for Measured Feature	Menu
2	Road	e.g. US10, MN210	Key-in
3	Mile Post	Indicates Numeric Value of Mile Post. Locations of quarter mile sections were estimated using vehicle odometer readings.	Key-in
4	Weed Species	Canada Thistle, Leafy Spurge, Poison Ivy, Other	Menu
5	Adjacent Land Use	Conservation Area, Row Crop, Pastureland, Wetland, Fallow Land, Forest, Residential, Commercial, Other	Menu
6	Landscape Position	Peak (also called Top Cut or Point of Intersection), In-slope, Ditch Bottom, Back-slope, Right-of-Way Line, Multiple Areas (see Figure 4)	Menu
7	Exposure to Sunlight	Direct Sunlight, Indirect Sunlight, Shade	Menu
8	Percent Cover	10-32, 33-65, 66-100%	Menu
9	Soil Type (Optional Input)	Visual determination of general soil type (e.g. sand, silt or clay). No field methods were applied.	Key-in
10	Misc. Soil Info (Optional Input)	Visual determination only (e.g. muddy area, discoloration).	Key-in
11	Surrounding/ Dominant Vegetation	Brome Grass, Cattails, Foxtail Barley, Legumes, Native Wild Flowers, Orchids, Reed Canary Grass, Spotted Knapweed, Switchgrass, Thistles, Wild Parsnip, Other	Menu
12	Misc. Vegetation Info	e.g. Discolored or Dying	Key-in
13	Recommended Treatment	Chemical, Mechanical, Biological	Menu
14	Management Obstacle/Issue	Dangerous Terrain, Migrating Weed Patch, Watershed, Chemical-resistant, Other	Menu
15	Radius	e.g. 4 feet; Point Data Only; Small Patches or Areas Not Accessible	Key-in
16	Obstacles	Tree, Shrub, Sign Post, Hazards/holes	Menu
17	Picture	Pictures were taken for record-keeping purposes. Indicate Road and Mile Post	Key-in
18	Comment	e.g. weather, indication grass was recently cut	Key-in


road:

mile post: -1.00

Species: Canada Thistle

Adjacent Land Use:

Landscape Position:

Exposure to Sunlight:

Percent % Cover:

Soil Type:

MISC Soil Info:

Vegetation:

MISC Vegetation:

Recommended Treatmnt: C

Mgmt Obstacle/Issues:

Comment:

Figure 1.1 An example of data entry form showing the drop-down menu (down arrow) and window for keying-in data.

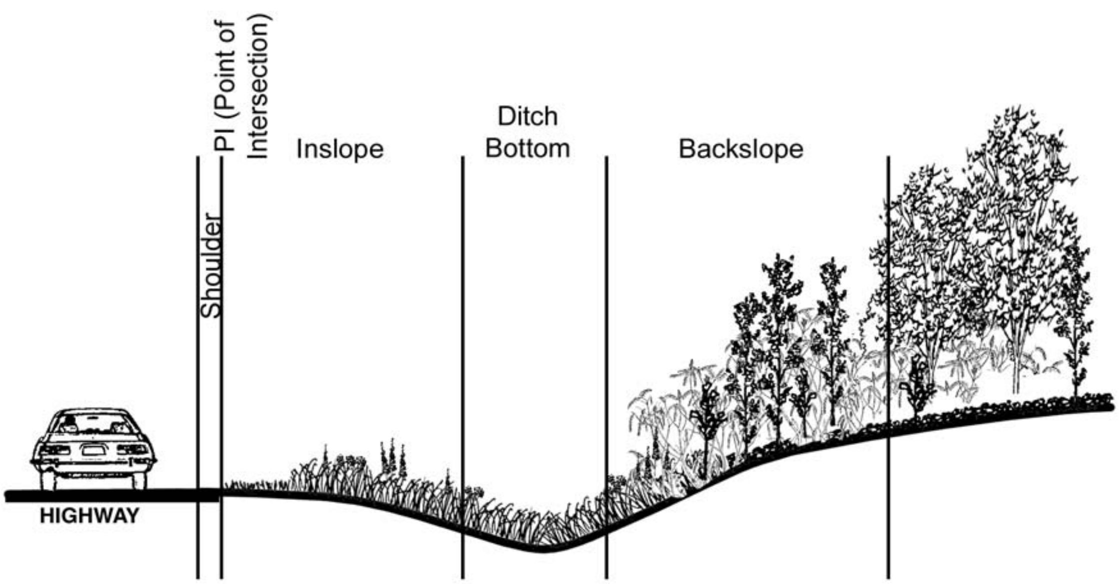


Figure 1.2 Image of right-of-way landscape positions with illustration of approximate contour line profile (Source: Mn/DOT).

Field surveys and data collection were conducted by both the Mn/DOT and U of MN personnel. To minimize possible errors due to the number of people involved in data collection, training was provided to all personnel prior to the field work, familiarizing them with:

2. GPS use - GPS concepts and operating platform
3. Proficiency with entry of qualitative data (e.g. estimating infestation densities)
4. Understanding attributes for which data is to be recorded (e.g. landscape positions, exposure to sunlight, etc.)
5. Identification of weed species, basic botany concepts
6. Definition of patch (minimum size set equivalent to an ATV, or 5ft by 8ft)
7. Highway safety protocols

Table 1.4 Sample of recorded GPS data exported to GIS with attributes species, adjacent landuse, Landscape position, percent cover, GPS-Date, -Time, -Week, and -Area, and comments.

Species	Adjacent_ Landuse	Landscape _ position	Exposure_ to sunlight	Percent_ cover	Max_ PDOP	GPS_ Date	GPS_ Time	GPS Area (acres)	Comments
Canada Thistle	Commercial	Back-slope	Direct Sunlight	10-32%	2.5	8/3/04	02:35: 20pm	0.000000	US10
Canada Thistle	Commercial	Back-slope	Direct Sunlight	10-32%	2.5	8/3/04	02:35: 20pm	0.018220	US10
Canada Thistle	Commercial	Back-slope	Direct Sunlight	10-32%	2.5	8/3/04	02:36: 22pm	0.006760	US10
….	….	….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….	….	….
Canada Thistle	Commercial	Ditch Bottom	Direct Sunlight	10-32%	2.0	8/3/04	02:43: 27pm	0.004845	US10
Canada Thistle	Commercial	Ditch Bottom	Direct Sunlight	10-32%	2.0	8/3/04	02:43: 27pm	0.000000	US10
….	….	….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….	….	….
Canada Thistle	Commercial	In-slope	Direct Sunlight	10-32%	2.2	8/3/04	02:54: 34pm	0.000072	US10
Canada Thistle	Commercial	In-slope	Direct Sunlight	10-32%	2.2	8/3/04	02:55: 04pm	0.000072	US10
Canada Thistle	Commercial	In-slope	Direct Sunlight	10-32%	2.2	8/3/04	02:59: 52pm	0.007621	US10
….	….	….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….	….	….
Canada Thistle	Commercial	In-slope	Direct Sunlight	33-65%	1.8	7/8/20 04	11:28: 16am	0.000001	
Canada Thistle	Commercial	In-slope	Direct Sunlight	33-65%	1.8	7/8/20 04	11:28: 16am	0.000001	
Canada Thistle	Commercial	In-slope	Direct Sunlight	33-65%	1.8	7/8/20 04	11:28: 16am	0.000000	

Chapter 2

Application of GPS in Surveys and Data Collection

Purpose: This chapter offers summary descriptions of the sampling designs, and procedures used in data collection and recording with the GPS units.

A weed patch was arbitrarily defined as a "contiguous infestation, larger than an all-terrain vehicle (approximately 5 x 8 feet), with infestation density of ten percent or more." Primary weed species of interest included Leafy Spurge, Poison Ivy and Canada thistle. Surveys were conducted during the months June though August (when species were in bloom for easier visibility and identification).

2.1 Experimental Design

Two experimental designs were adopted in the field surveys. The first method employed 7, 3-mile segments, adopted by the Mn/DOT District 4 in their sampling surveys initiated in 2000. The design specified surveying the same fixed-position segments every year. The second survey design, which was developed in the current project, involved use of 100 ¼-mile segments, selected randomly. The methods of sample selection for the new design differed, as already explained in chapter 1.

2.1.1 3-Mile Procedure

Data was recorded at 7, 3-mile segments of highways in District 4. The surveys were conducted in these fixed three-mile segment locations beginning 2000 till the end of the study in summer 2005.

Weed position and distribution along roadways were mapped and data recorded using Trimble® Pro XR GPS unit. The person doing the survey walked or drove around each infestation patch, with spatial and all attribute data recorded in the GPS units. Infestations patches too small to walk were mapped by recording them as a 'spot' position, the approximate radius recorded in the GPS. All data was recorded following the form/template provided by the data dictionary.

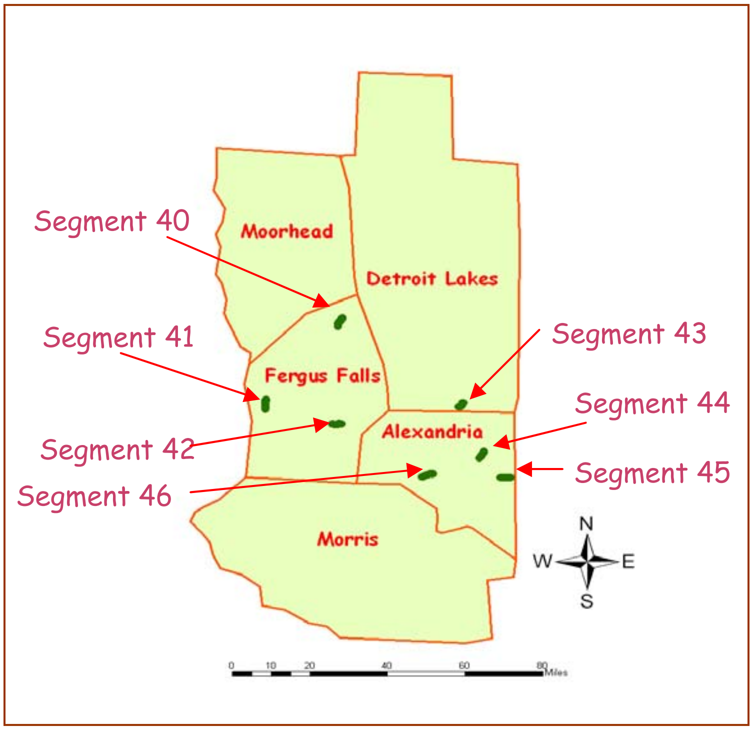


Figure 2.1 Location of the 7, 3-mile segment (segments 40-46) in 5 management sub-areas of Mn/DOT District 4.

2.1.2 Quarter-Mile Procedure

This sampling design was more intensive, having adopted a larger number of small size (1/4-mile) sampling units. The design was used in the 2004 and 2005 field surveys. Samples of 103 and 101, 1/4-mile segments were selected and adopted in the surveys conducted in summer of 2004 and 2005, respectively. Mn/DOT personnel were responsible for surveys in all three-mile segment sites and 75% of the quarter-mile segment sites. The Mn/DOT personnel conducted the field work using the 4-wheel all-terrain-vehicles. These were driven around the perimeter of each weed patch (figure 6), or took point data, with data recorded in the handheld GPS units. In areas too dangerous for ATV use, data collection was completed by walking the site, or simply taking strategic point data.

Figure 2.2 Mn/DOT employee shown on all-terrain-vehicle with GPS unit.

The University of Minnesota personnel surveyed the remaining 25% of the quarter-mile segment sites by walking around each patch, while recording coordinate and all other attributes information using handheld GPS units (Figure 2.3).

Figure 2.3 U of MN staff member walking in Canada thistle patch, and recording information in a GPS unit.

Chapter 3

GPS Data Post-Processing

Purpose: This chapter presents descriptions of procedures followed in cleaning, correcting,, processing, and finally, export of GPS data into GIS environment.

3.1 Cleaning and Correction

Data recorded in GPS units was downloaded into the computer using the GPS Pathfinder Office (version 3.0) software (see Appendix A). First, hand editing is needed to remove user errors, or gaps in the satellite coverage. All raw data files require examination of point and polygon boundaries, looking for obvious errors during data collection. Examples may include sharp angles delineating the area of an infestation, or multiple measurements taken in the same location indicated by erratic polygon boundaries (see Figure 3.1). Errors may be removed by using the erase function in the Pathfinder software. This function allows the operator to erase individual or blocks of positions (vertices) which create the lines displayed. The purpose of the editing is to obtain a more representative area and shape of the weed infestation. After hand editing, polygons should have relatively smooth curvatures. Polygons will never have perfect shapes, due to the manual collection of data. The extent of editing required rests solely with the user.

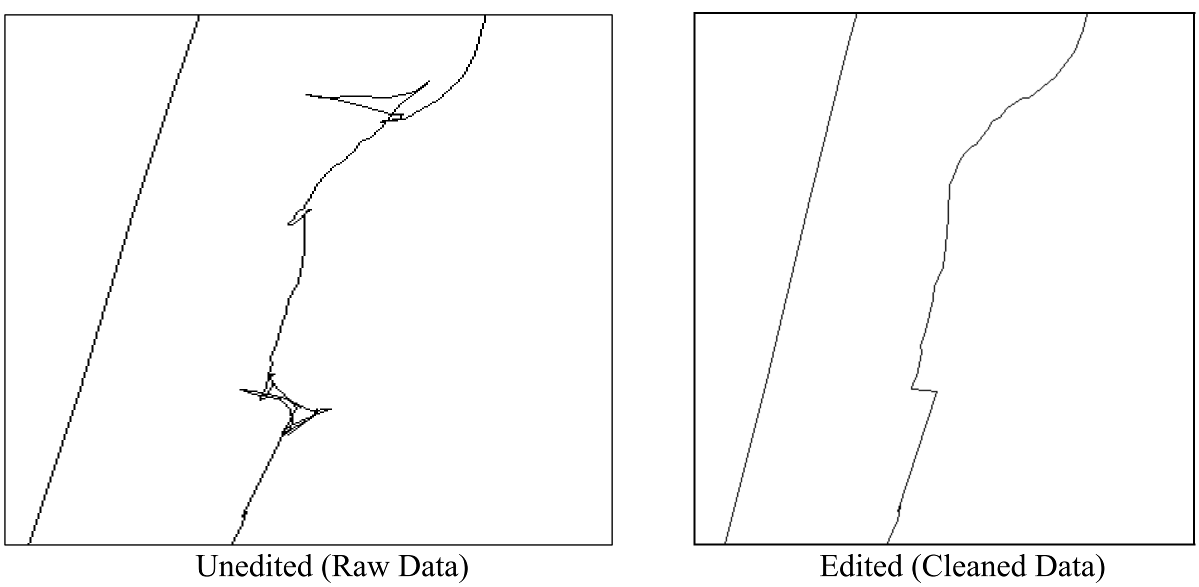


Figure 3.1 Errors are removed from the raw data file, creating a more realistic representation of the true shape of the polygon.

Unfortunately, protocols are difficult to establish for editing in the Pathfinder software due to the visual nature of the data. However, suggestions follow regarding potential protocols and training.

- An individual or group may decide on what is "editable" creating standards. Specific examples detailing before and after editing (e.g. Figure 3.1) may be incorporated during training.
- Best results would be achieved if individuals involved with data collection "cleaned" their own data files. Field personnel will be more likely to notice obvious misrepresentations of field conditions.
- It is recommended that the data cleaning operation be conducted as soon as possible after the data collection exercise when the information on areas surveyed, unique circumstances, etc., are still fresh in mind.

A differential correction is then applied to the GPS data. This correction is necessary because GPS data may include positional uncertainty. Differential correction is based on collecting a set of base files from a base station, which is at a precisely known location, within 12 hours of the rover files being collected. The base files are selected from the closest beacon station. Differential correction involves calculating error in the satellite signals, by finding the difference between the positions calculated from the satellite signals and the known reference position. The resulting differential corrections can be used to remove much of the positional error from the rover file data. Differential correction was performed both in "real time" (Figure 3.2) during data collection, and also post-processed for all data collected (Figure 3.3). Once differential correction is applied, new corrected files are generated. *(Source: http://courses.unt.edu/hwilliams/GPS/differential.htm)*

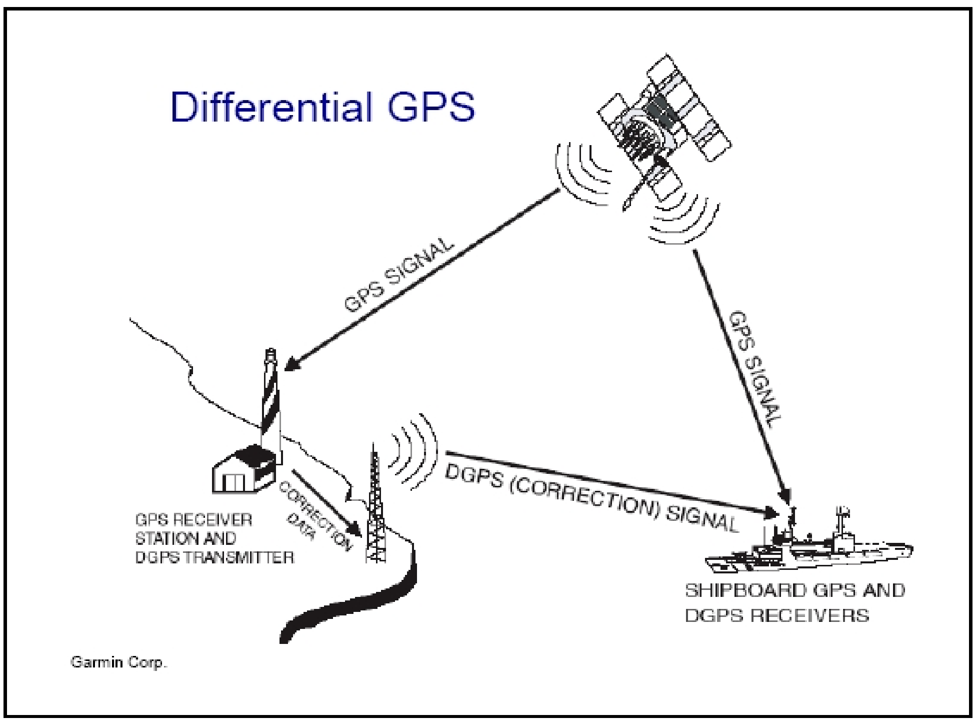


Figure 3.2 Illustration of "real time" differential correction.

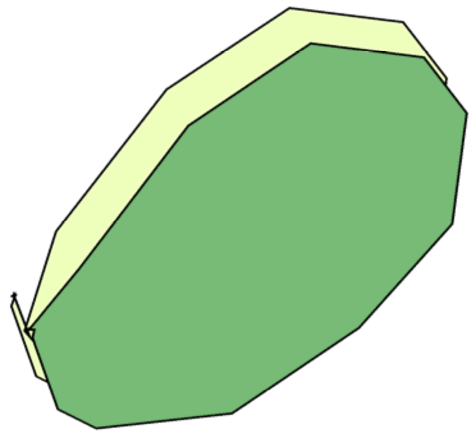


Figure 3.3 An example of the spatial impact of differential correction. The differentially corrected polygon (dark or dark green) is shifted slightly southeast compared to the uncorrected polygon (light or light green).

3.2 Export to GIS

After raw data files have been hand edited and undergone differential correction, files may be exported from Pathfinder as shapefiles. The following spatial information may remain the unchanged once set in the GPS unit, and should be initially synchronized then verified in the Pathfinder software (see Figure 11) before exporting:

- Coordinate System: Universal Transverse Mercator (UTM)
- Zone: 15 North
- Datum: North American Datum (NAD) 1983 (Conus)
- Coordinate Units: Meters

Note: The coordinate data listed is specific to the Mn/DOT – District 4 project, and may change depending on location.

During the export operation, pertinent attributes should be selected (Click on 'Properties', select attributes by 'Checking' boxes of all attributes you want). Some of the required attributes to be exported in the data include: Species, Percent _cover, Adjacent Land Use, GPS Area, and others. These attributes will form the core variables in the weed infestation analysis. This export allows the files to be used in a GIS, such as ArcGIS 9.1 used in this project. An array of GIS operations may be performed on the shapefiles to produce the output for further processing and statistical analysis (see Appendix A).

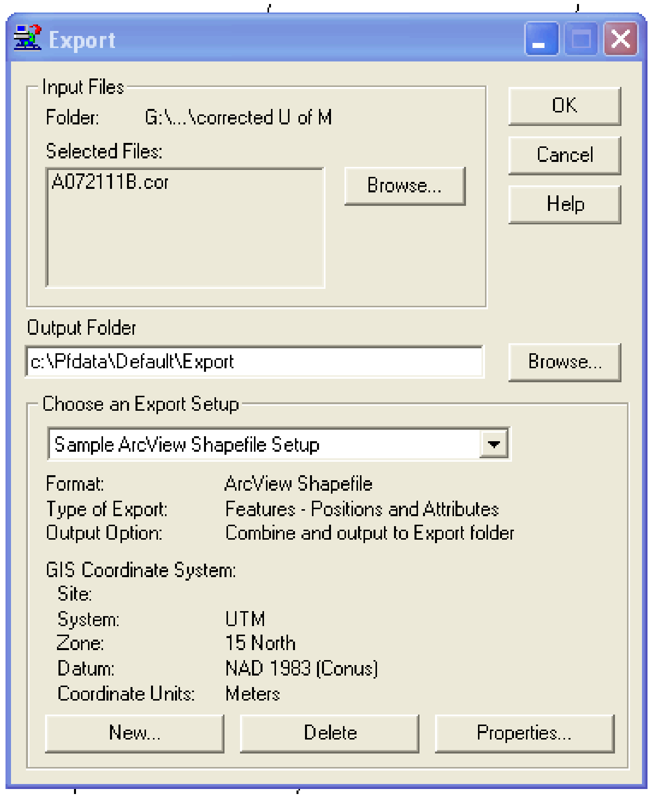


Figure 3.4 Export window in Pathfinder software.

Chapter 4

Analysis of Data in GIS Environment

Purpose: This chapter presents the step-by-step approach for incorporating GPS data into a GIS, to produce output for data analysis.

When GPS files are corrected and exported, two file types may be created: Plot and Spot. This is true when surveys were conducted and data recorded using both spatial data types. The plots are the spatial data recorded for patches (area exceeding 5 x 8 square feet) of weed infestations mapped by walking around and recording coordinates using GPS units. Spot files contain single point recordings for patches less than the pre-determined area. One measurement is taken at the location, and the approximate radius recorded. Spot files are represented as points in ArcGIS, while plots are polygons. Separate files are created during Export process for polygon and point data.

Where there is need to group these files together a feature class is first to be created. Using the 'Append' function, multiple polygons (plot), and multiple Point (spot) files may be combined into one large project (see Figure 4.1). These combinations centralize the data and simplify file structure. However, prior to combining spot and plot data, it will be necessary o first convert the spot data into polygons by creating buffers around each spot. The size of the buffer will be equal to the recorded radius of the mapped infestation.

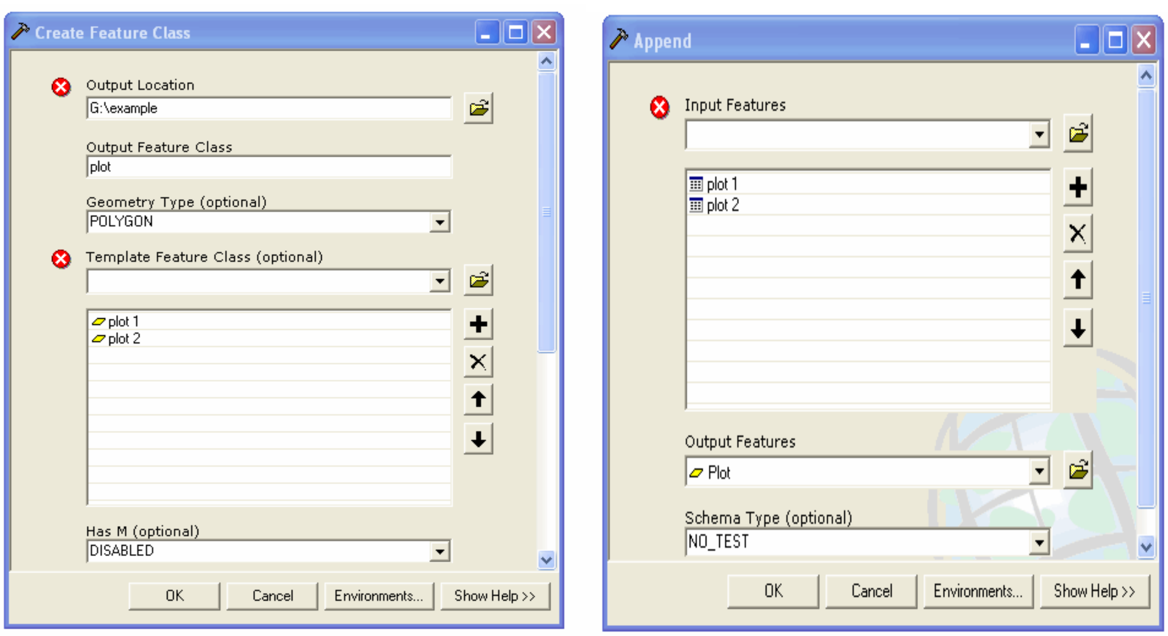


Figure 4.1 Feature Class and Append windows of ArcGIS.

As previously discussed, field personnel recorded approximate radii of small-sized weed patches. A field is added to the attribute table of the spot shapefile, where the radius measurement in meters is converted to feet. The radii values were applied in the GIS operation, “Buffer” (Figure 4.2), creating an area around each spot the size of its radius.   . In creating the buffer, point data is transformed into polygons, and shape area calculated using XTools Pro (an ArcGIS extension), results displayed in a column in the data table.

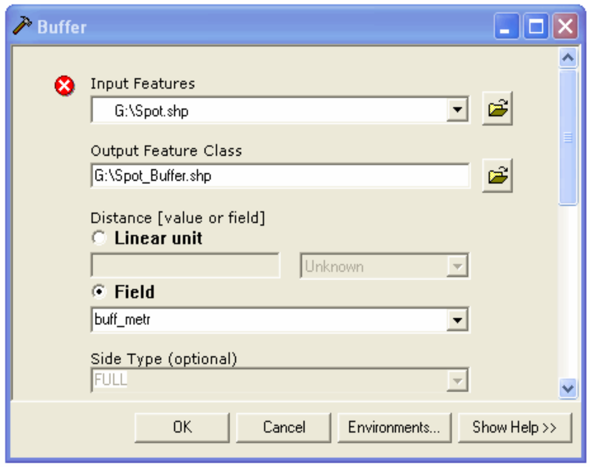


Figure 4.2 Buffer window of ArcGIS.

Using the buffered spot shapefile (now polygons) and the existing plot shapefile, create a feature class, and then append the two files. The result is one file containing both spot and plot polygons (suggested file name: plotandspot). See Appendix A. The spot and plot shapefile is then intersected with the ecozone boundaries. This intersection assigns the ecozone name (e.g. Red River Prairie) for every polygon (weed patch) in the file.

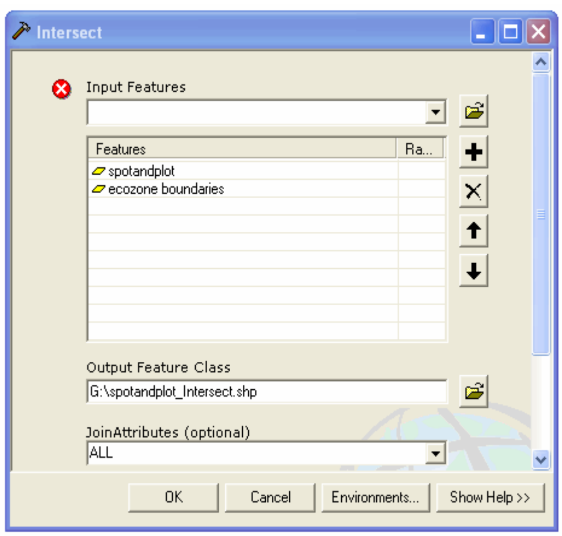


Figure 4.3 Intersect window of ArcGIS, and layer of ecological zones in Mn/DOT District 4.

The new shapefile (plotandspot_intersect) next undergoes a dissolve function (see Figure 4.3). The dissolve removes overlapping boundaries; ensuring areas of overlap will not be counted twice.

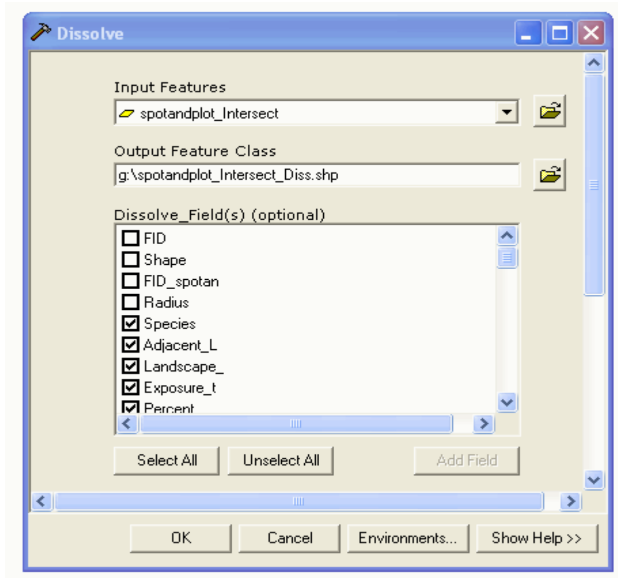


Figure 4.4 Dissolve window in ArcGIS.

Dissolve fields include: Species, Adjacent Landscape (Adjacent_L), Landscape Position (Landscape_), Sunlight Exposure (Exposure_t), Percent of Area Infested (Percent) and Ecozone Name (Subsecname). The dissolve fields determine the attributes considered as the dissolve is performed.

With the dissolve completed (plotandspot_interesect_diss), the data is ready for area calculations. X-Tools Pro (an extension in ArcGIS) has an array of functions, and may be used in determining area (acres, hectares) and/or perimeters of polygons representing weed patches mapped (see Figure 4.4).

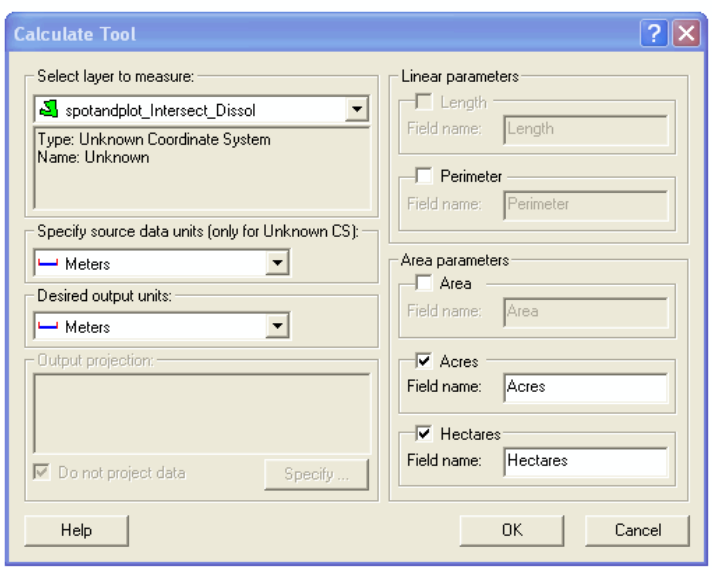


Figure 4.5 Calculate tool window of X-Tools Pro within ArcGIS.

Additional fields will need to be added to the final attribute table. Fields include segment, segment type, acres-per-mile factor and acres-per-mile.

4.1 Segment Identification

Segment numbers are assigned for each polygon within the final shapefile. All 3-mile segments have been previously numbered 40-46 by Mn/DOT District 4. To identify all segments, a distinguishing field name (such as SegmID) should be added in the attribute data table. Select "text" as the data type. Select all polygons data for each 3-mile segment using "select features" in the toolbar. Assign IDs (40-46) through the "calculate values" feature accessed by right-clicking on the attribute table column title (SegmID). Quarter-mile SegmID can be assigned by overlaying the weeds infestation layer with one of the survey site locations
.
Quarter-mile segment IDs are a combination of GIS route name and mile marker (e.g. I94_30). This notation represents Interstate 94 at mile marker 30.

Segment Type

3-mile and ¼-mile segment types.

4.1.1 Acres-per-Mile Factor

The acres-per-mile factor enables a calculation of the acres-per-mile within a study area. This factor incorporates the number of sections within a quarter or three-mile segment. For example, a divided highway would contain three sections within the segment: one along each shoulder of the road and one dividing the lanes of traffic. The three-mile segments numbered 40-44 and 46 were not divided highways. Therefore, a total of 6 miles encompassed each segment, and a factor of 1/6 was assigned. Segment #45 is a divided highway, and a factor of 1/9 assigned. All quarter-mile segments along Interstate 94 and US 10 (divided highways) are assigned a factor of 1/0.75. All remaining quarter-mile segments are located along undivided highways and assigned a factor of 1/0.5.

4.1.2 Acres-per-Mile

Acres-per-mile may be calculated by multiplying acres and acres-per-mile factor.

Chapter 5

Application of Small Sample Survey Data in Weed Management

Purpose: Describe procedure followed in the adaptation of data recorded in small samples' surveys to estimate infestations over larger areas.

Appendices B, C and D provide detailed guidance on performing data analysis. The reader is provided with definitions of terminology and examples of data generated in various computations.

5.1 Processing Survey Data to Determine Miles of Infested Highways ROWs

Appendix C describes the procedures ("hatching") adopted in the sectioning of rights-of-way into smaller (1/20th-mi and 1/250th-mi long) by 5 meters wide cells, to facilitate (a) testing the relationship between infestations and landscape positions in roadways, and (b) estimate miles of roadway ROW infested by given species. This data could make possible predicting likelihood of species occurring in ROWs landscape positions. The information is important in planning and procurement of control measures.

5.2 Application of Survey Data in Planning and Requisition of Treatments for Large Areas

Managers require certain pertinent information to arrive at decisions on:

- types of treatments to employ, as well as on methods of their application in control noxious species,
- estimated quantities of required materials for control of noxious species

Sampling surveys offer economic alternatives to costly inventories for acquisition of critical information on extent of infestations, necessary for managers to make these decisions, and the ability to quantify required treatments.

The surveys data may be applied in conducting estimations on, for example, the volume of herbicides needed for control of known noxious species in Mn/DOT's District 4. It is possible to use similar analysis to apportion treatment at sub-divisional level, including ecological zones, sub-districts or district-wide. This data is valuable to Managers in conducting estimates on cost of treatments in area of choice (ecological zone, sub-district, or district-wide). Further, the data may facilitate evaluation of Economic Cost analysis for any of the adopted treatments. This is further discussed in the Appendix B of this document.

5.3 Application of 1/20th-mile segments size in future surveys:

The findings of the current project recommend the need for inclusion differences in types of highway (with or without median) during selection of sampling sites. This is because highways with a median have generally larger right-of-way area than those without a median.

Table 5.1 illustrates arrangement of highway mile posts, at 1/250-mi intervals. Highways with median have a 1 in the column on Type of Highway, while those without median have a 0. Selection of sampling sites per ecological region is carried out following the stratified random selection design.

Table 5.1. Sample population of reference posts at 1/20th-mile intervals in the Mn/DOT managed highways in District 4.

Ecological Zone	GIS_ ROUTE	Type of Highway (1=divided, 0=undivided)	REF_POST (1/20th mi intervals)	1/20th mi segmID
Red River Prairie	I94	1	1.000	I94_1.000
Red River Prairie	I94	1	1.050	I94_1.050
…	…	…	…	…
Minnesota River Prairie	MN104	0	13.250	MN104_13.250
Minnesota River Prairie	MN104	0	13.300	MN104_13.300
Minnesota River Prairie	MN104	0	13.325	MN104_13.325
Minnesota River Prairie	MN104	0	13.375	MN104_13.375
…	…	…	…	…
Pine Moraines & Outwash Plains	MN113	0	1.550	MN113_1.550
Pine Moraines & Outwash Plains	MN113	0	1.600	MN113_1.600
Pine Moraines & Outwash Plains	MN113	0	1.650	MN113_1.650
…	…	…	…	…

Chapter 6

Procedures for sampling roadways

Purpose: This section details procedures adopted in conducting surveys for estimating weed infestations along highway rights-of-way in Mn/DOT District 4. The procedures may be adopted to provide best estimates of infestation in the larger areas, with minimum variance and lower surveying cost.

Operational sampling

Sampling by Mn/DOT staff is designed to evaluate their current roadside noxious weed control program and to budget for following year's operations/activities. Efficacy is indicated by acres of right-of-way infested by the more abundant kinds of weeds, or by percentage of acres that are infested by rarer ones. The procedures outlined below will estimate acres per roadway mile occupied by any weed species, and has been developed using District 4 as a pilot district. The procedures can be used in other districts, but will need to be modified to accommodate the different ecozones and roadway miles in the other districts.

Sample units. The basic sample unit will be a 225 ft (75 paces) segment of roadway, including all non-paved parts of rights-of-way along both sides of pavement and median if present. In District 4, there are 16,332 locatable segments, identified by road number, milepost and 10ths of a mile in between. Road markers are divided into 10ths because they can be located easily from mileposts using a vehicle odometer. For example, reference point "MN200-66.2" would be on state highway 200, and begin 2/10ths of a mile from milepost 66 toward milepost 67. A master list of all possible segment reference points is compiled in the Excel spreadsheet "D4MasterMilePostList.xls."

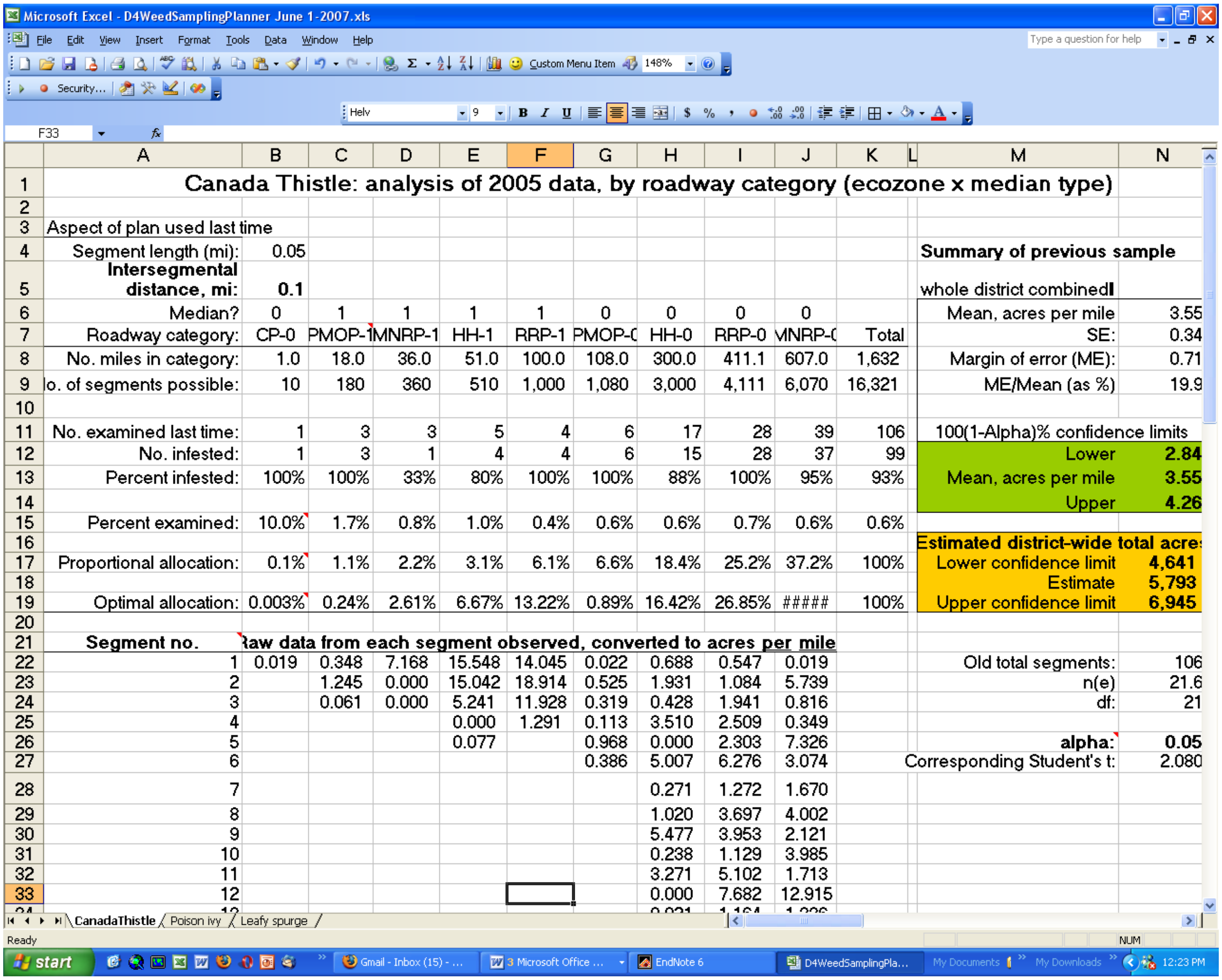
Stratification of roadways. In a given year, a subset or sample of the listed segments needs to be examined, and this sample will be chosen as a stratified random sample chosen from points in nine roadway categories. The categories are defined by as a combination of ecozone and absence (-0) or presence (-1) of median: Chippewa Plains-0; Hardwood Hills-0, -1; Minnesota River Prairie-0, -1, Pine Moraines and Outwash Plains-0, -1; and Red River Prairie-0, -1. Here and in the associated data files, these categories are abbreviated as acronyms, for example, CP-0, HH-0, *etc*. Previous sampling in 2004 and 2005 indicated acres per mile of Canada thistle, poison ivy and leafy spurge varied substantially among categories, which indicates that stratifying by category will both assure coverage and improve district-level precision.

Determination of numbers of segments per road category. A sample will consist of a chosen number of segments (n = 100, or otherwise). That total will be distributed among the nine roadway categories using the spreadsheet, "WeedSamplingPlanner.xls." The spreadsheet enables one to assign sampling sites to the 9 categories proportional to number of roadway miles in the category. Once numbers per category are chosen, the actual set of segments to be examined will be chosen from the reference point list in

"D4RoadMarkerList.xls" using functions and procedures available in Microsoft Excel. A new sample should be drawn each year, based the previous year's sampling survey data. A sampling plan for the upcoming year should be based on the previous year's sampling survey data. Once entered into the planner spreadsheet, managers can explore changes in total number of segments and their optimal distribution for the upcoming year.

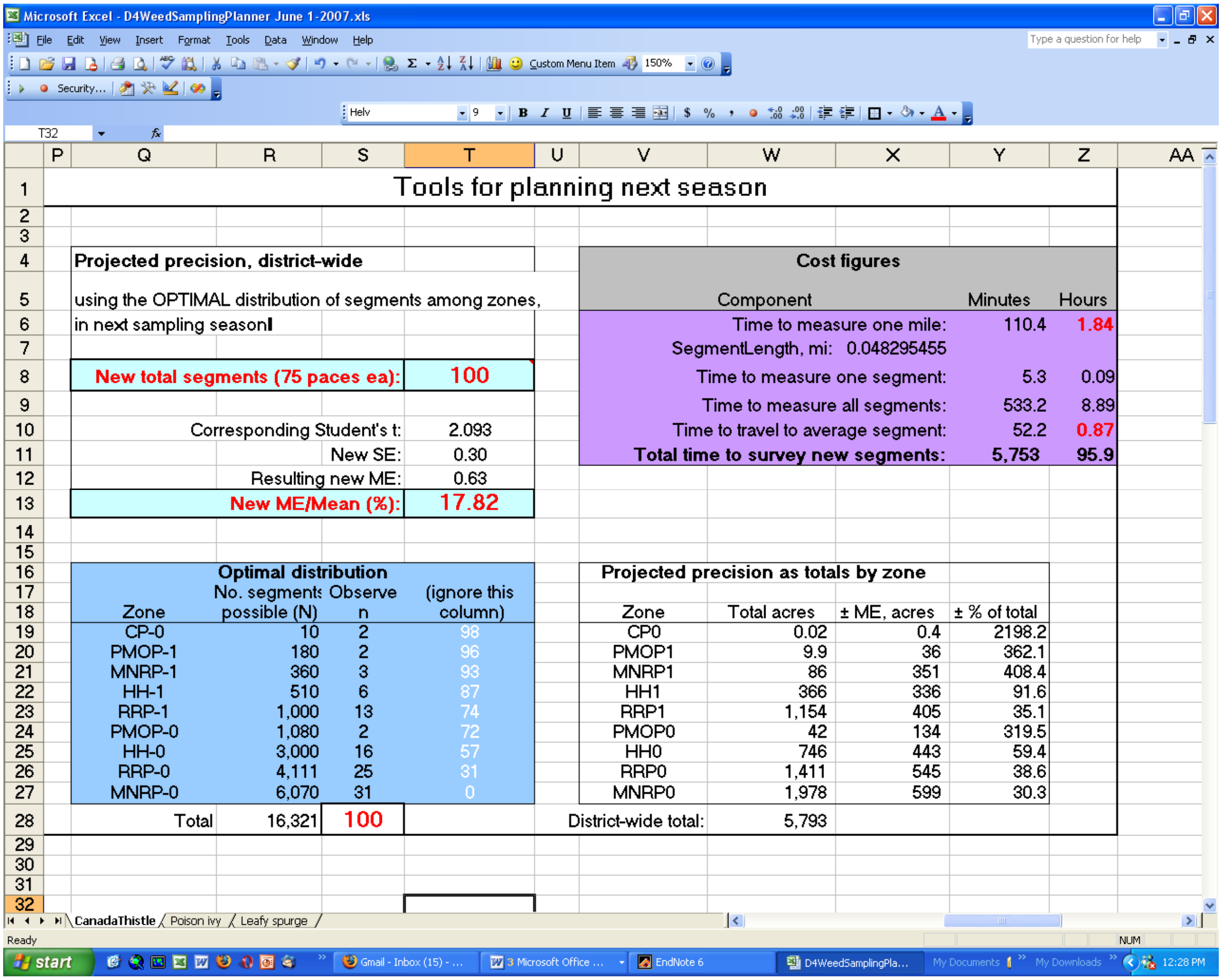
6.1 Steps for finding out how many segments to examine in each of the nine road categories:

1. Open the spreadsheet "WeedSamplingPlanner.xls", screen shot in Figures 6.1a and 6.1b. This spreadsheet contains three worksheets, one for each of the three species surveyed in 2005. Each worksheet (a) summarizes past measurements, in acres per roadway mile, and calculates summary statistics by roadway category; (b) projects achievable precision for a new, revised district-wide total number of segments; and (c) calculates the optimal distribution for the new segments among the nine categories. The best distribution for one species is likely to be different from one for another species, because the optimal distribution is based in part acres per mile and variability, which differ among weed species. It is recommended that results for Canada thistle be used to define the district's sampling plan, because that species is the driving problem.
2. Within the planner, use trial and error, substituting different values for "New total segments (75 paces each):", cell T8, and see resulting changes in "New ME/Mean (%):", cell T13, and "Total time to survey new segments:", cell Z11. Settle upon a new total, based on achievable precision, total sampling cost, or a compromise between the two.
3. The target number of segments (*n*s) for a new survey will be listed automatically, by road category, in the section "Optimal distribution," cells S19-S27. Subject to the constraint that a minimum of two segments should be chosen from every category, the optimal distribution of the new total will produce the smallest, district-wide margin of error for the estimated mean acres per mile.



	A	B	C	D	E	F	G	H	I	J	K	M	N
1	Canada Thistle: analysis of 2005 data, by roadway category (ecozone x median type)												
2													
3	Aspect of plan used last time												
4	Segment length (mi):	0.05										**Summary of previous sample**	
5	**Intersegmental distance, mi:**	**0.1**										whole district combined	
6	Median?	0	1	1	1	1	0	0	0	0		Mean, acres per mile	3.55
7	Roadway category:	CP-0	PMOP-1	MNRP-1	HH-1	RRP-1	PMOP-0	HH-0	RRP-0	MNRP-0	Total	SE:	0.34
8	No. miles in category:	1.0	18.0	36.0	51.0	100.0	108.0	300.0	411.1	607.0	1,632	Margin of error (ME):	0.71
9	No. of segments possible:	10	180	360	510	1,000	1,080	3,000	4,111	6,070	16,321	ME/Mean (as %)	19.9
10													
11	No. examined last time:	1	3	3	5	4	6	17	28	39	106	100(1-Alpha)% confidence limits	
12	No. infested:	1	3	1	4	4	6	15	28	37	99	Lower	**2.84**
13	Percent infested:	100%	100%	33%	80%	100%	100%	88%	100%	95%	93%	Mean, acres per mile	**3.55**
14												Upper	**4.26**
15	Percent examined:	10.0%	1.7%	0.8%	1.0%	0.4%	0.6%	0.6%	0.7%	0.6%	0.6%		
16												**Estimated district-wide total acres**	
17	Proportional allocation:	0.1%	1.1%	2.2%	3.1%	6.1%	6.6%	18.4%	25.2%	37.2%	100%	Lower confidence limit	**4,641**
18												Estimate	**5,793**
19	Optimal allocation:	0.003%	0.24%	2.61%	6.67%	13.22%	0.89%	16.42%	26.85%	#####	100%	Upper confidence limit	**6,945**
20													
21	**Segment no.**	**Raw data from each segment observed, converted to acres per mile**											
22	1	0.019	0.348	7.168	15.548	14.045	0.022	0.688	0.547	0.019		Old total segments:	106
23	2		1.245	0.000	15.042	18.914	0.525	1.931	1.084	5.739		n(e)	21.6
24	3		0.061	0.000	5.241	11.928	0.319	0.428	1.941	0.816		df:	21
25	4				0.000	1.291	0.113	3.510	2.509	0.349			
26	5				0.077		0.968	0.000	2.303	7.326		**alpha:**	**0.05**
27	6						0.386	5.007	6.276	3.074		Corresponding Student's t:	2.080
28	7							0.271	1.272	1.670			
29	8							1.020	3.697	4.002			
30	9							5.477	3.953	2.121			
31	10							0.238	1.129	3.985			
32	11							3.271	5.102	1.713			
33	12							0.000	7.682	12.915			

Figure 6.1a Screen shot of spreadsheet "WeedSamplingPlanner.xls" applied in selection of number of samples (at X), and the corresponding measurement error (at Y) for adoption in surveying for Canada thistle in highways rights-of-way, 2005.



New total segments (75 paces ea):	100
Corresponding Student's t:	2.093
New SE:	0.30
Resulting new ME:	0.63
New ME/Mean (%):	17.82

Cost figures		
Component	Minutes	Hours
Time to measure one mile:	110.4	1.84
SegmentLength, mi: 0.048295455		
Time to measure one segment:	5.3	0.09
Time to measure all segments:	533.2	8.89
Time to travel to average segment:	52.2	0.87
Total time to survey new segments:	5,753	95.9

Optimal distribution			
Zone	No. segments possible (N)	Observe n	(ignore this column)
CP-0	10	2	98
PMOP-1	180	2	96
MNRP-1	360	3	93
HH-1	510	6	87
RRP-1	1,000	13	74
PMOP-0	1,080	2	72
HH-0	3,000	16	57
RRP-0	4,111	25	31
MNRP-0	6,070	31	0
Total	16,321	100	

Projected precision as totals by zone			
Zone	Total acres	± ME, acres	± % of total
CP0	0.02	0.4	2198.2
PMOP1	9.9	36	362.1
MNRP1	86	351	408.4
HH1	366	336	91.6
RRP1	1,154	405	35.1
PMOP0	42	134	319.5
HH0	746	443	59.4
RRP0	1,411	545	38.6
MNRP0	1,978	599	30.3
District-wide total:	5,793		

Figure 6.1b Screen shot of spreadsheet "WeedSamplingPlanner.xls" applied in selection of number of samples (at X), and the corresponding measurement error (at Y) for adoption in surveying for Canada thistle in highways rights-of-way, 2005.

6.2 Steps for selecting the specific 225-feet segments to be examined:

1. Make a working copy of the file "MarkerListMaker.xls" (Table 6.0), open the new copy, and select the worksheet "MasterMilePostList.xls" (Table 6.1)."

2. Freeze the values in all columns, labeled "Category" through "Rand()." The first three columns contain values linked in from D4RoadMarkerList.xls, and those in Rand() are produced by Excel's RAND() function. All will be "hot" when the spreadsheet is opened. To freeze the current values, select all four columns (A-D), then "Edit…Copy," then "Edit…Paste Special…Values" to paste current values over the selected columns. After pasting, new segment information and random numbers can only be obtained by opening a new copy of the original "RoadListMaker.xls."

3. Reorganize the master list by sorting with Excel's Sort procedure to find the segments to be used. These are the ones with the lowest random numbers. Select all columns in "MasterMilePostList.xls" and then use "Data…Sort" to execute a nested sort of segments within each of the nine road categories. Under "Data…Sort", click on Sort by <Road category> (ascending) and Then by <RAND()> (ascending). This will sort the segments within each category into ascending random order. Once completed, delete the entire "Rand()" column, which will no longer be needed.

4. Extract the labels for the chosen segments and place them into a second worksheet where they can be reorganized for field work. For each of the nine categories, select and Copy the desired number of segments (as determined with WeedSamplingPlanner.xls), starting at the top of each category's list, and then paste those rows into the "SelectedOnes" worksheet. These segments are the ones to be surveyed.

3. Resort the extracted list by SubDistrict and Hwy-Post.tenth, to organize them in a way that may be more convenient to drive to and map.

Table 6.1 A sample of MasterMilePostList.xls of all 1/10th mile marker positions in all Mn/DOT managed highways in Mn/DOT's District 4.

SubDistrict	Category	Hwy-RefSpot	Rand()
Moorhead	CP-0	MN200-066.7	0.531154513
Moorhead	CP-0	MN200-066.6	0.131366825
Moorhead	CP-0	MN200-066.9	0.56504457
Moorhead	CP-0	MN200-066.5	0.629575066
Moorhead	CP-0	MN200-066.3	0.891649185
Moorhead	CP-0	MN200-066.1	0.176906205
Moorhead	CP-0	MN200-066.4	0.571308127
Moorhead	CP-0	MN200-066.8	0.700500158
Moorhead	CP-0	MN200-066.2	0.51997975
Moorhead	CP-0	MN200-066.0	0.881789959
Moorhead	HH-0	US59-252.2	0.873391915
Alex	HH-0	MN108-057.6	0.961389494
Fergus	HH-0	MN34-010.2	0.133192115
Fergus	HH-0	MN32-003.9	0.074960966
Alex	HH-0	MN29-098.8	0.104877655
Fergus	HH-0	MN108-029.7	0.092010557
Fergus	HH-0	US59-238.0	0.493614205
Moorhead	HH-0	MN87-000.9	0.178254138
Alex	HH-0	MN27-077.2	0.298102744
Alex	HH-0	MN114-019.9	0.610672741
Alex	HH-0	MN235-005.7	0.651763465
Alex	HH-0	MN29-072.4	0.606316012
Moorhead	HH-0	MN34-040.8	0.600532103
Moorhead	HH-0	MN34-045.6	0.777136031
Alex	HH-0	MN27-082.4	0.90691321
Fergus	HH-0	MN108-033.2	0.270803834

Table 6.2 A sample of MasterMilePostList.xls of all 1/10th mile marker positions in all Mn/DOT managed highways in Mn/DOT's District 4.

SubDistrict	Category	Hwy-RefSpot	**Ecol. zone**	**Median**	**RoadNum**	**Easting**	**Northing**	**MP.10th**
Moorhead	CP-0	MN200-066.0	CP	0	MN200	306892.0	5244502.4	66.0
Moorhead	CP-0	MN200-066.1	CP	0	MN200	306892.0	5244502.4	66.1
Moorhead	CP-0	MN200-066.2	CP	0	MN200	306892.0	5244502.4	66.2
Moorhead	CP-0	MN200-066.3	CP	0	MN200	306892.0	5244502.4	66.3
Moorhead	CP-0	MN200-066.4	CP	0	MN200	306892.0	5244502.4	66.4
Moorhead	CP-0	MN200-066.5	CP	0	MN200	306892.0	5244502.4	66.5
Moorhead	CP-0	MN200-066.6	CP	0	MN200	306892.0	5244502.4	66.6
Moorhead	CP-0	MN200-066.7	CP	0	MN200	306892.0	5244502.4	66.7
Moorhead	CP-0	MN200-066.8	CP	0	MN200	306892.0	5244502.4	66.8
Moorhead	CP-0	MN200-066.9	CP	0	MN200	306892.0	5244502.4	66.9
Alex	HH-1	I94-093.0	HH	1	I94	301583.8	5088350.8	93.0
Alex	HH-1	I94-093.1	HH	1	I94	301583.8	5088350.8	93.1
Alex	HH-1	I94-093.2	HH	1	I94	301583.8	5088350.8	93.2
…	…	…	…	…	…	…	…	…
Fergus	HH-0	MN108-023.8	HH	0	MN108	278644.0	5158412.6	23.8
Fergus	HH-0	MN108-023.9	HH	0	MN108	278644.0	5158412.6	23.9
Fergus	HH-0	MN108-024.0	HH	0	MN108	280214.3	5158338.3	24.0
Fergus	HH-0	MN108-024.1	HH	0	MN108	280214.3	5158338.3	24.1
Fergus	HH-0	MN108-024.2	HH	0	MN108	280214.3	5158338.3	24.2
Fergus	HH-0	MN108-024.3	HH	0	MN108	280214.3	5158338.3	24.3
Fergus	HH-0	MN108-024.4	HH	0	MN108	280214.3	5158338.3	24.4
Moorhead	HH-0	MN228-003.3	HH	0	MN228	289330.9	5170839.5	3.3
Moorhead	HH-0	MN228-003.4	HH	0	MN228	289330.9	5170839.5	3.4
Moorhead	HH-0	MN228-003.5	HH	0	MN228	289330.9	5170839.5	3.5
Moorhead	HH-0	MN228-003.6	HH	0	MN228	289330.9	5170839.5	3.6
Moorhead	HH-0	MN228-003.7	HH	0	MN228	289330.9	5170839.5	3.7
Moorhead	HH-0	MN228-003.8	HH	0	MN228	289330.9	5170839.5	3.8
…	…	…	…	…	…	…	…	…

Segment processing. To process each segment, begin by recording the examiner's name, time of arrival, and GPS coordinate of front of vehicle. Next, scout the segment quickly to determine if the entire right-of-way can be mapped. If accessible, walk with traffic 75 paces (225 ft) and place a road marker to designate the end of the segment; the front of the vehicle will mark its beginning. While returning to the vehicle, scout the same roadway edge to plan how to map it.

Map the segment by tracing (into GPS unit) the locations of weed patches or locations of isolated specimens. Do this for each noxious weed species. A patch is defined as a sprayable area occupied by a single species, two or more paces in longest dimension. Patches may be dense or sparse, but level of infestation will be disregarded. For the purpose of estimating chemical and applicator needs, sprayable area seems more meaningful than actual coverage area.

Map patches of each species. If patches of different species overlap, then trace around each one separately. If a given species is present, but specimens are isolated or in patches smaller than 2 paces long, then record the species as a dot on the map. When areas are collated, spots will be assigned an area of 3 square feet.

Complete this mapping procedure from pavement to edge of right-of-way, on both sides of the pavement, and in the median if present. When done, record time of departure.

If a chosen segment can not be mapped? A chosen segment may be inaccessible, because of flooding, construction or anything else. If so, then substitute a nearby replacement by continuing down the road and stopping at the next nearest accessible spot. On the SelectedOnes list, record the reason why the original one was unavailable, and record the GPS coordinates and "Hwy-Post.tenth" location of the substitute section that was actually examined.

Data produced. After maps are processed (Chapters 3 and 4), Mn/DOT should be able to extract the following:

a. Who surveyed a set of segments, and when they left "home" and began surveying
    i. For each segment,
    ii. Time/date of arrival
    iii. GPS coordinate and Segment Highway-milepost.tenth
    iv. Comment concerning accessibility, and if not, why not.
b. If mapped, then for each weed species,
    i. Species ID, total acres as sum (patch areas) plus spots, on both sides of roadway, and in median if present.
    ii. Time/date of departure
    iii. Time and date of return "home."

Surveyor IDs, arrival times and departure times will allow us to reconstruct the timeline of each surveyor's activities, and allow Mn/DOT to get reliable estimates of average traveling time between segments, and of average processing time per segment.

Measured areas of each of the different weed species from the current survey can then be entered into the D4WeedSamplingPlanner spreadsheet, to update the district's database, and revise a previously used plan for sampling in the next year.

Table 6.3 Summary statistics for abundance of three noxious weeds along roadways in District 4, as sampled with seven 3-mi road segments in 2004 and 2005.

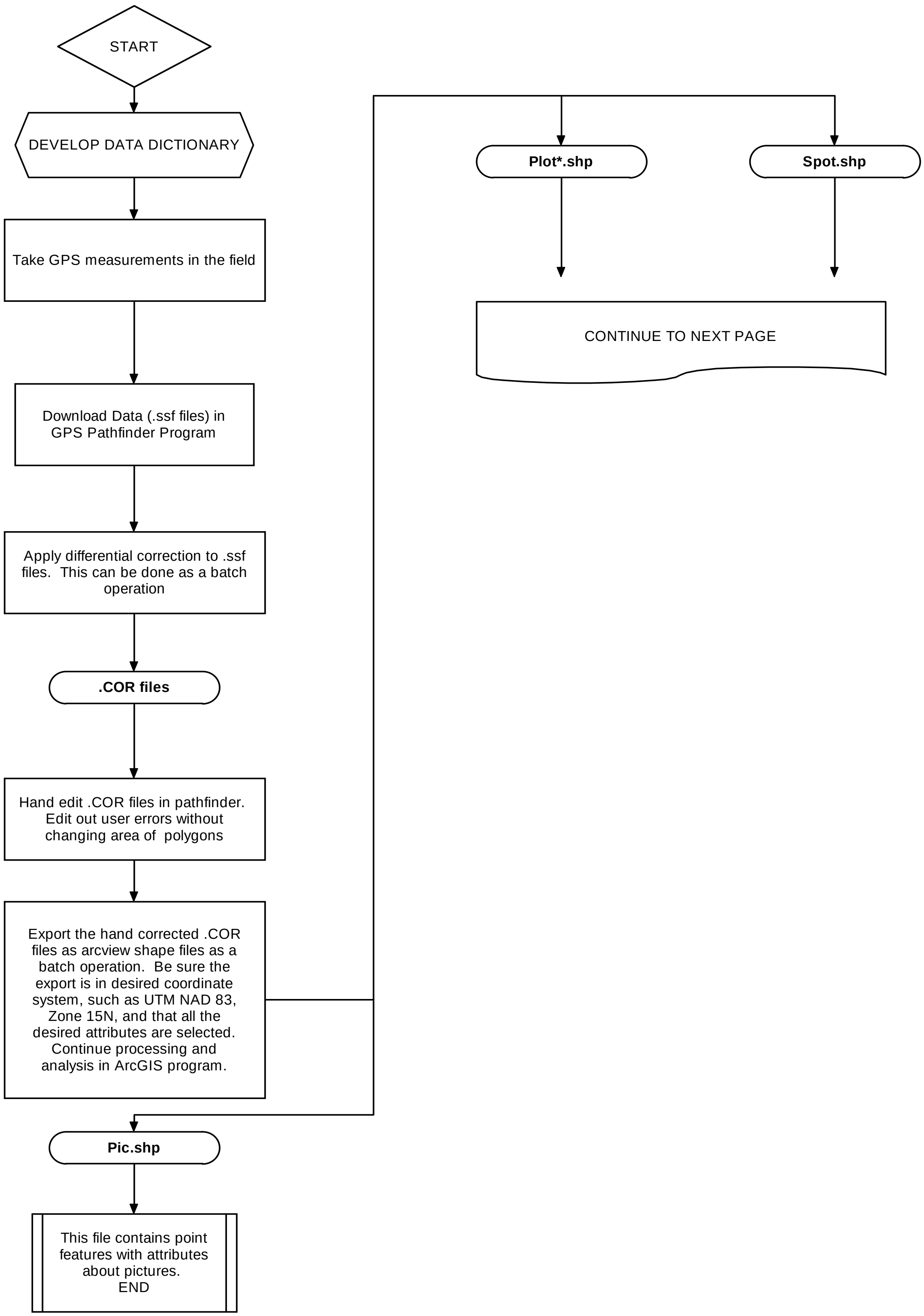
Species	Year	No. segments infested (of 7)	Mean (acres -per mile)	Variance
Canada thistle	2004	7	1.041	0.662
	2005	7	2.375	16.030
Poison ivy	2004	4	0.117	0.062
	2005	3	0.115	0.052
Leafy spurge	2004	3	0.04352	0.00433
	2005	4	0.00386	0.00004

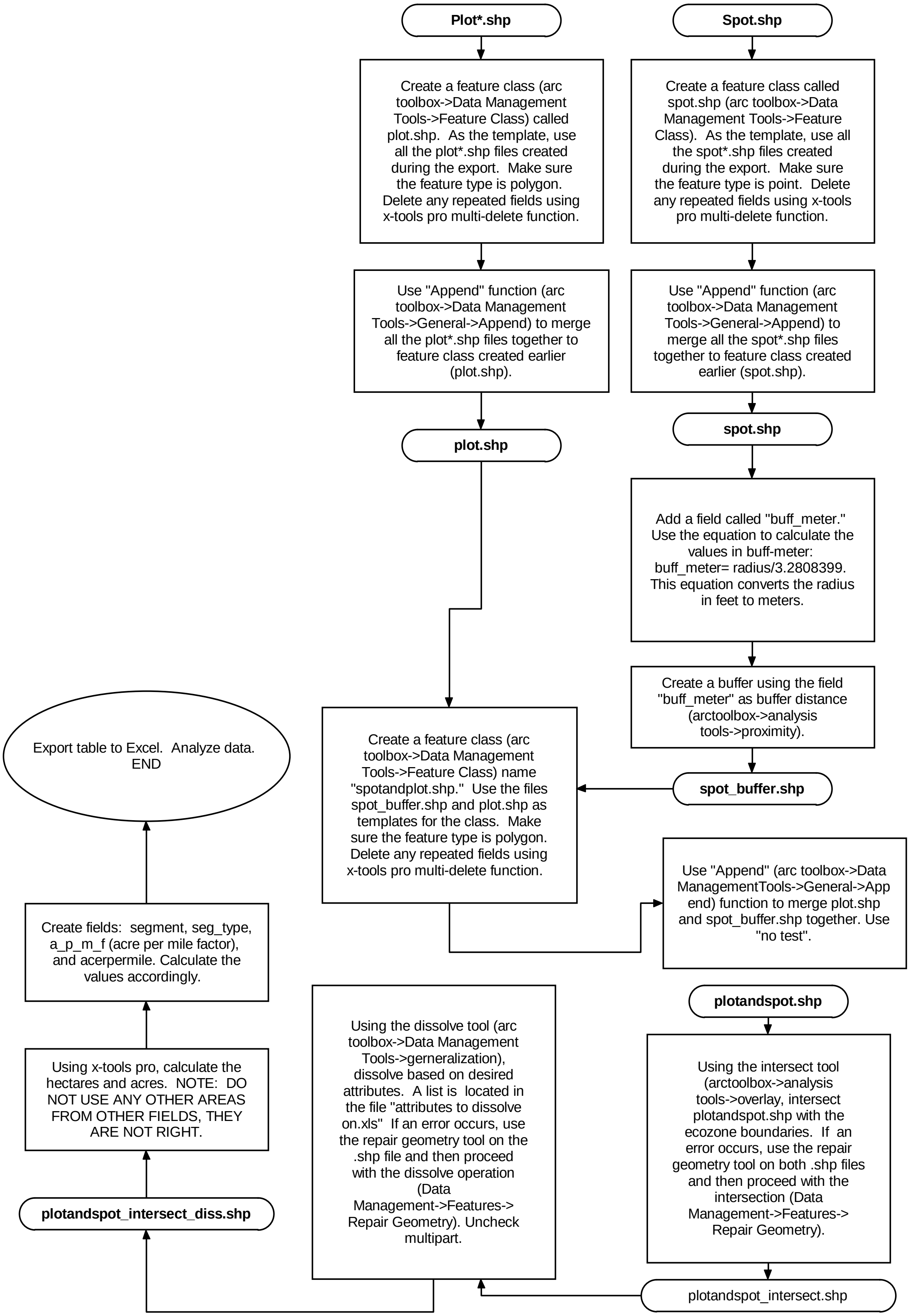
Table 6.4 Sample comparative analysis illustrating influence of segment length on surveying efficiency (the efficiency shown by higher relative net precisions, RNPs, BOLD), estimated with N = 10,000 re-samplings of infested ¼-mi. segments.

			2004			2005		
Species	Segment length (mi)	Survey Time Hrs/unit	Acres per mi	Variance	RNP*	Acres per mi	Variance	RNP
Canada thistle	0.1	0.186	1.040	2.351	**2.29**	2.374	19.079	**0.28**
	0.5	0.93	1.034	1.616	0.67	2.372	17.541	0.06
	1	1.86	1.040	1.144	0.47	2.369	16.939	0.03
Poison ivy	0.1	0.186	0.207	0.361	**14.88**	0.204	0.357	**15.1**
	0.5	0.93	0.206	0.203	5.28	0.204	0.203	5.3
	1	1.86	0.206	0.167	3.22	0.205	0.166	3.2
Leafy spurge	0.1	0.186	0.104	0.122	**44.14**	0.007	0.002	2339
	0.5	0.93	0.102	0.041	26.11	0.007	0.000	**2536**
	1	1.86	0.101	0.022	24.52	0.007	0.000	2524

Appendix A: Process Flow for GPS and GIS Data Analysis

Process Flow for GPS and GIS Data Analysis




Plot*.shp
Create a feature class (arc toolbox->Data Management Tools->Feature Class) called plot.shp. As the template, use all the plot*.shp files created during the export. Make sure the feature type is polygon. Delete any repeated fields using x-tools pro multi-delete function.
Use "Append" function (arc toolbox->Data Management Tools->General->Append) to merge all the plot*.shp files together to feature class created earlier (plot.shp).
plot.shp
Spot.shp
Create a feature class called spot.shp (arc toolbox->Data Management Tools->Feature Class). As the template, use all the spot*.shp files created during the export. Make sure the feature type is point. Delete any repeated fields using x-tools pro multi-delete function.
Use "Append" function (arc toolbox->Data Management Tools->General->Append) to merge all the spot*.shp files together to feature class created earlier (spot.shp).
spot.shp
Add a field called "buff_meter." Use the equation to calculate the values in buff-meter: buff_meter= radius/3.2808399. This equation converts the radius in feet to meters.
Create a buffer using the field "buff_meter" as buffer distance (arctoolbox->analysis tools->proximity).
spot_buffer.shp
Create a feature class (arc toolbox->Data Management Tools->Feature Class) name "spotandplot.shp." Use the files spot_buffer.shp and plot.shp as templates for the class. Make sure the feature type is polygon. Delete any repeated fields using x-tools pro multi-delete function.
Use "Append" (arc toolbox->Data ManagementTools->General->Append) function to merge plot.shp and spot_buffer.shp together. Use "no test".
plotandspot.shp
Using the intersect tool (arctoolbox->analysis tools->overlay, intersect plotandspot.shp with the ecozone boundaries. If an error occurs, use the repair geometry tool on both .shp files and then proceed with the intersection (Data Management->Features-> Repair Geometry).
plotandspot_intersect.shp
Using the dissolve tool (arc toolbox->Data Management Tools->gerneralization), dissolve based on desired attributes. A list is located in the file "attributes to dissolve on.xls" If an error occurs, use the repair geometry tool on the .shp file and then proceed with the dissolve operation (Data Management->Features-> Repair Geometry). Uncheck multipart.
plotandspot_intersect_diss.shp
Using x-tools pro, calculate the hectares and acres. NOTE: DO NOT USE ANY OTHER AREAS FROM OTHER FIELDS, THEY ARE NOT RIGHT.
Create fields: segment, seg_type, a_p_m_f (acre per mile factor), and acerpermile. Calculate the values accordingly.
Export table to Excel. Analyze data. END

Appendix B: Weed Population Questions and Definitions of Terminology

Weed Population Questions and Definitions of Terminology

KEY TO TERMS:

The following are definitions to terms used in the descriptions and evaluation of weed infestation in Mn/DOT's District 4 highways rights-of-way (ROWs), using survey data recorded in this project. There are large differences in the widths of ROWs over different roads, hence significant differences in total area (acres) of ROW per unit road distance. For purposes of this data analysis, we have categorized the highways in the study area into two classes: divided and undivided. Divided highways are those roads with a vegetated section or median separating the lanes running in opposite directions. Divided highways are generally the larger interstates with multiple lanes; they would normally possess larger fence-line to fence-line widths, hence would have larger ROW area than of the undivided roads. Figure 1 offers an illustration of these categories of highways.

1. Road miles: There are two terms we have used to refer to distances between any two points along given highway(s):

    a. Linear Miles (M) – This term has been used in reference to road length between points A and B traveling in one direction (Figure B1) In the scope of this project, the term refers to the total road miles of the unpaved areas fenceline-to-fenceline (including median where available) in a given highway, going one direction.

    b. Road Edge Miles (M_{edge}) – This term has been used to refer to the sum of miles of unpaved area between two points (A and B), in a highway. This is obtained by summing up the lengths of 'unpaved areas (left, right and median where available) bordering the highway pavement in the region of concern. In a divided highway (I-94, figure 1), total distance between point A and B is the sum of the length (X) for the left side, the right side, and the median for this road, or 3X . For an undivided roadway (137th street NW, Figure B1), the total Road Edge Miles is equal to the sum of the left and right sides of the road, or 2X'. Road Edge Miles is equivalent (approximately) to the distance a boom sprayer travels between point A and B (or A' and B'), during weed control operations, assuming one run per side of the road or median.

2. a). Mean Infested ($\overline{X}$), Acres/Linear Mile. This refers to the average weed infestation in a given region (ecological zone, management sub-district or District 4), and has been evaluated as:

    $$\overline{X} = \frac{\sum A}{L}$$

    where:
    A = Total area (acres) of surveyed ROW infested by a given weed species
    L = Total Linear Miles of surveyed highway ROW (miles)

    The $\overline{X}$, A and L values are evaluated separately for:

- Ecological zone in Mn/DOT's District 4
- Management Sub-district of Mn/DOT's District 4
- Whole Mn/DOT's District 4

b). Grand Mean Infested (G$\overline{X}$), Acres/Linear Mile: This is the overall mean for the entire District 4, and was evaluated as follows:

(i) Quarter Mile Segments Survey. Selection of sampling sites in this survey was done by stratification by ecological zones. The number selected in each ecological zone was proportional to total miles of Mn/DOT managed roads in the zone. Hence, grand mean calculation takes into account this weighting factor as per equation below:

$$G\overline{X} = \sum_{i=1}^{n} \overline{X}.\frac{L_{SEi}}{L_{EZi}}$$

where n is total number of ecological zones in the study area (District 4)
L_{SEi} = Total Linear miles surveyed in ecological zone i
L_{EZi} = Total Linear Miles of Mn/DOT Managed roads in ecological zone i

(ii) 3-Mile Segments Survey

$$G\overline{X} = \frac{\sum_{i=1}^{n} A_i}{n}$$

Where A_i is the total area (acres) infested in ecological zone, i
L_{SEi} = Total Linear miles surveyed in ecological zone i
L_{EZi} = Total Linear Miles of Mn/DOT Managed roads in ecological zone i

3. Total Area Infested (T), acres. This is the total area (acres) of ROW infested by given species, and is evaluated for per ecological zone, management sub-district or District 4 as:
   $T = \overline{X}.M$
   where M is the total Linear Miles for the region of concern

4. Total Infested Miles (T_i). This is the total distance within surveyed roadway ROWs which is infested by a given weed species. We evaluated this by summing up the Road Edge miles of the survey sites in the ecological zone, management sub-district or District 4 infested per weed species. This was accomplished in the project by first dividing the highways ROWs into 65.6 feet (20 meter) long sections (S_{20m}) traversing each road-side (and median in divided highways). All sections infested by given weed species were then summed up and total distance (T_i, miles) evaluated using relation:

$$T_i = \frac{20\sum_{i}^{n} S_{20m}}{1600}$$

   where 1600 is the number of meters per mile, and *n* is the total number of 65.6 feet (20 meter) long sections in the road sides of all surveyed sites in a given ecological zone, management sub-district or District 4.

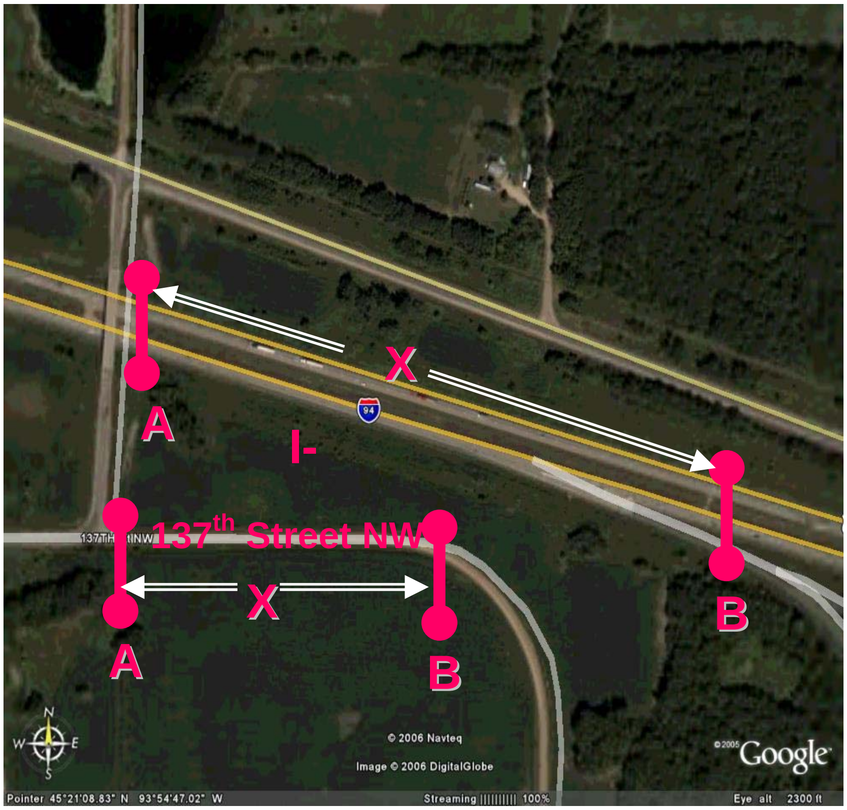


Figure B1: Illustration of road miles in: Divided (I-94) and undivided (137th street NW) roads.

Mn/DOT District 4 weed population questions to be addressed in the analysis of data

1. When using the 3-mile Mn/DOT weed sampling system, what are the calculated mean infested acres per road mile for the three weed species? Using this mean calculate how many total acres are infested by the three weeds in Mn/DOT District 4.
2. When using the 0.25mile weed sampling system, what is the calculated mean infested acres per road mile of the three weed species within each ecological region and the calculated grand mean infested acres per road mile of the three species for the entire region. Using these means what is the total acres infested by the three weeds in Mn/DOT District 4, in each Mn/DOT sub-district, and each ecological region in the District 4.
3. Do calculations using the grand mean from the 3-mile DOT sampling system and the grand mean from the 0.25 mile system and give projections of the total acres infested by the three weeds? How do these grand mean projections compare to projections made with the eco-region means using the 0.25 mile sampling method.
4. Compare the level of variance in data collected with the 3-mile method and the 0.25 mile method.
5. When using the 0.25mile (0.50 or 0.75 total road edge miles) weed sampling system, what is the infested road-edge miles infested with weeds requiring spraying with a full boom spray? If using a spray boom how many acres would be treated.

6. How much of the area sprayed could be reduced if sections of the spray boom could be shut off within the road-edge miles treated.
7. How many road-edge miles and acres per mile are infested by each weed species for each landscape position of highway right-of-way (peak, in-slope, ditch bottom and back-slope
8. Run statistical models to evaluate the impact of sample number and sample size on variance. Develop matrix of sampling cost and variance to aid Mn/DOT personnel in selection of appropriate sample number and sample size to meet their management needs. Evaluate cost of information versus the returns on investment.

Appendix C: Processing Weeds Data into 20 Meter Segments and 20 X 5 Meter Sections

Processing Weeds Data into 20 Meter Segments and 20 X 5 Meter Sections

Processing weeds data into 20 meter (65 feet) segments

One of the tasks to be accomplished is determining total linear miles in highway rights-of-way (ROWs) which are infested by each of the three weed species: Canada thistle, leafy spurge and poison ivy. This will be accomplished by dividing all the District 4 highway ROWs into 20 meter long segments. Executing the Intersection operation in ArcGIS of the weeds data layer with this segment layer will facilitate assigning infestation patches to each of the 20 meter segments. Utilizing simple calculations, a count of infested 20 meter segments will produce road edge miles infested.

<u>Weeds Data</u> *<Plotsandspot_Intersect_Diss.shp>*

This will be the data layer obtained through the processes described in the flow diagram, Appendix A.

<u>Road Segments Data</u> *<D4_AllHwys_Hatch_Buffd_Int_Disso.shp>*

This data layer will be processed through the following steps:
Acquire the District 4 trunk highways data (*D4_AllHwys.shp*). Using ArcGIS tools, divide ROWs of these roads into segments, starting with placing hatch marks at specified intervals along the roadways. ArcGIS will normally place the hatch marks, starting at the node with the lowest mile post value in each roadway. A two lane road will have mile post markings on each of the trunk ways. These markings may not necessarily match along the entire road length, resulting in mismatched hatch marks. This will, later in the process, result in segments not matching the required size. A possible solution is deleting all second lines (such as occur in divided highways) and any extra road lines such as service roads and ramps. Deletion of a second line in a divided highway can be accomplished in a one-step process. While in Editor Mode, Open Attribute -> Options -> Select by Attributes ->Route_Dir. Select either D or I route direction (recommend I) then press <Delete> key to clear the line. Save and exit Editor.

<u>Creating Hatch Marks:</u>

According to ArcGIS Help, hatching is a type of labeling that is designed to post and label hatch marks or symbols at a regular interval along measured linear features. These are mainly for display purposes and not for inclusion into the data layers, but can be converted to a shape file for inclusion as a layer.

<u>Hatching features in a layer</u>

1. Right-click the layer in the table of contents that you want to hatch and click "Properties".
2. Click the "Hatches" tab.
3. Check "Hatch features" in this layer.

4. Type an appropriate hatch interval. The roads data layer has units of miles; to place hatch marks at 65 feet, give interval of 0.012, equivalent to 1/80th of a mile, where 20 m = 65 feet.
5. Click “Hatch Placement” tab and specify Distance Units as meters. Click Ok.
6. Click “Hatch Def(1)”.

   The Hatch Definition view becomes active.

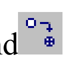
7. Type an appropriate hatch line length (300 meters to cover maximum possible right-of-way area in any of the highways).
8. Click on “Hatch Orientation” and check “Center”. Hatch marks will then be centered along road line.
9. Right-click the hatch class and click “Add End Hatch Definition”.

   The End Hatch Definition view becomes active.

10. Type an appropriate End hatch tolerance if necessary (not necessary).
11. Type an appropriate Line length (0, no need to display end of line hatches).
12. Check “Label these hatches” if necessary (It is not necessary, leave unchecked).
13. Click OK.

<u>Adding the Convert Hatches to Graphics command</u>

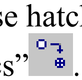
1. From the ArcMap Tools menu, click “Customize”.
2. Click the “Toolbars” tab.
3. In the Toolbars list, click “Context Menus”.
   The Context Menus toolbar appears.

4. Click the “Context Menus” menu and click “Feature Layer Context Menu”.
5. Click the “Commands” tab.
6. Click “Linear Referencing” in the Categories list.
7. Click the “Save” in dropdown arrow and select location for where you want your customization saved.
8. Drag the “Convert Hatches To Graphics” command  to the “Feature Layer Context” Menu.
9. Click Close.

Tip

- You can convert hatches to graphics so that they can be moved, resized, and edited on the map.

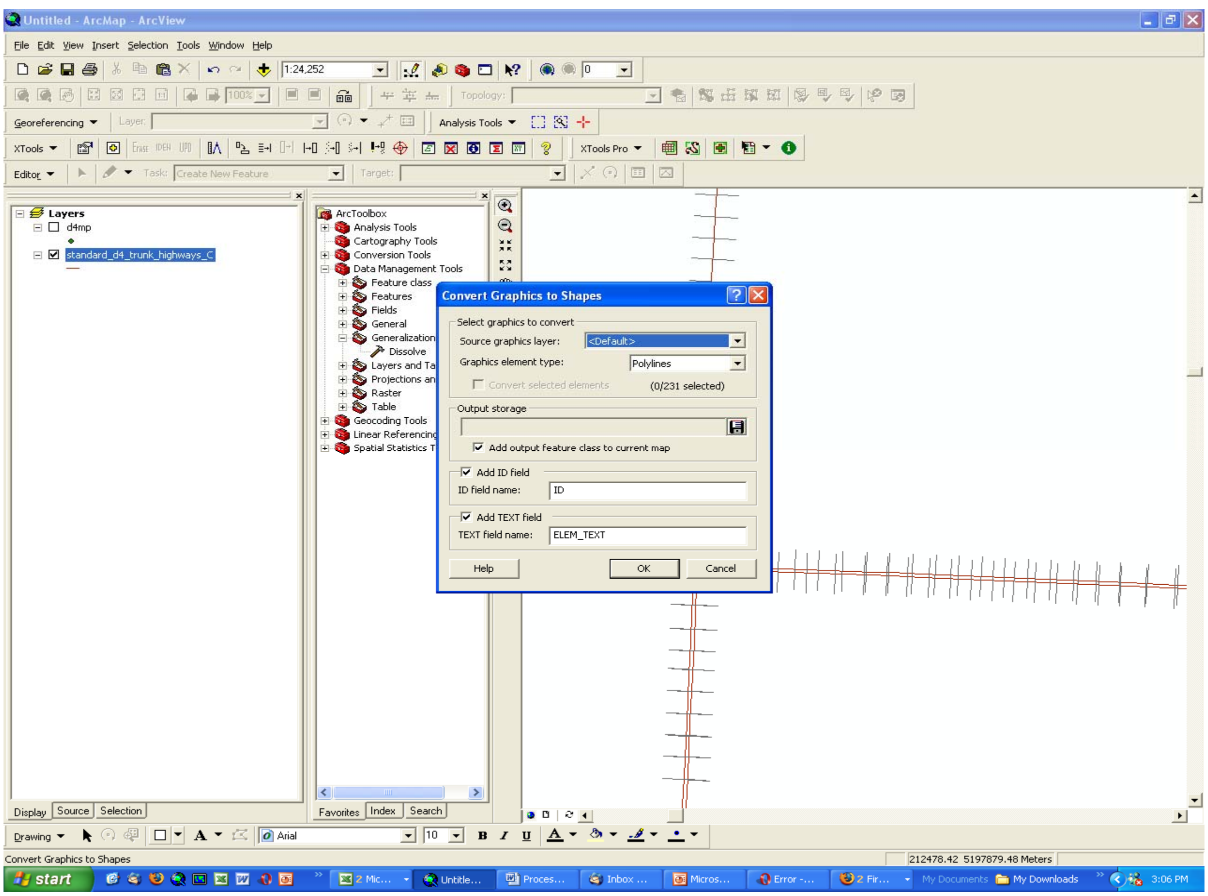
<u>Converting hatches to graphics</u>

1. In the ArcMap table of contents, right-click the layer whose hatches you want to convert to graphics and click “Convert Hatches to Graphics” .
2. Click the features for which you want to create graphics.
3. Uncheck any hatch classes you do not want converted to graphics if appropriate.
4. Click the Target annotation group dropdown arrow and select the annotation target listed (using the default name) you want to add the graphics to.

5. Alternately, type the name of a new target annotation group (e.g. hatch_march2006).
6. Click OK.

Converting hatches graphics to Shapefile

1. In the ArcMap Toolbar, click on "XPro Tools" (if activated; if not activated, in the Menu Bar, click on Tools, select Extensions, check the XTools Pro check box)
2. Select "Feature Conversions", then "Convert Graphics to Shapes".
3. In the drop down menu, select the Source Graphics Layer you just created. This layer will be a Polyline.
4. Click on diskette shape icon to specify output storage folder and file name.
5. Click Ok.
6. The created hatches shapefile will appear automatically in the Table of Contents and be among displayed layers
7. Create Polygon layer out of this polyline by creating buffers around each hatch mark.
8. From ArcToolbox, select "Analysis Tools", click on "Proximity", select "Buffer".
9. In Input Feature, browse for hatch marks Polyline layer. Specify storage filename and folder
10. Enter buffer distance (half the distance between hatch marks, 8 meter). From drop down menu, specify units as meters.
11. Click Ok. New polygon layer will be added to table of contents and displayed upon completion of process.



Dissolve:

To eliminate possibility of duplicate polygons, use ArcToolbox to dissolve by given feature.

1. Click on "XTools Pro", select "Table Operations", then "Add X, Y, Z Coordinates".
2. Select the correct layer (Hatch Marks Polygon Layer)
3. Un-check the "Add Z Coordinate" box
4. Click Ok
5. On completion of processing, open the attribute table of the layer to verify X and Y coordinates have been added.
6. Click on "ArcToolbox".
7. Select "Data Management Tools".
8. Select "Generalization", then double click on "Dissolve".
9. Input Feature, Browse for the correct file (Hatch Marks Polygon Layer)
10. Enter Output Feature Class filename *<D4_AllHwys_Hatch_Buffd_Int_Disso.shp>*
11. From the list of Dissolve_Fields, check the box for X (or Y) coordinates.
12. Click Ok.

A new layer will be added to Table of Contents and displayed. Use this layer to execute an Intersection Overlay with the weeds data layer (*<Plotsandspot_Intersect_Dsso.shp>).*

Segmenting roadway rights-of-way (ROW) to 20 x 5 meter sections

To facilitate detailed evaluation of highway rights-of-way (ROWs), we sectioned all road miles (1,630 linear miles) in the study area into units 20 meters long by 5 meter wide (65.6 feet long by 16.4 feet wide). This operation resulted in formation of a grid of 20 x 5 meter segments populating different landscape positions of the highway ROWs. The purpose of this operation was to determine total road edge miles infested by target weed species at each of the landscape positions. The landscape positions corresponded to consecutive strips located at 5 meter (16.4 feet) intervals, starting from the roadway centerline (see Figure 1). These 5 meter intervals were established to approximately correspond to the width of individual sections of boom sprayers used by Mn/DOT in its weed management operations.

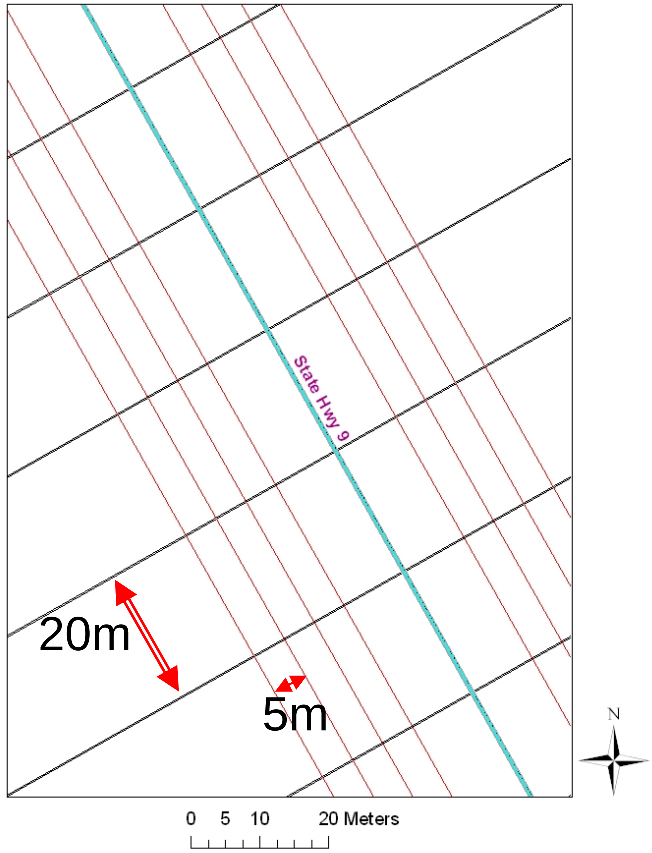


Figure C1: Illustration of segmentation of highway (State Highway 9) right-of-way into 20m by 5m segments.

To construct this layer of 20m by 5 m segment units required overlaying as well as further processing of layers ***D4_AllHwys_Hatch_Buffd_Int_Disso.shp*** (created in operations previously described in this Appendix), and the trunk highways, ***D4_AllHwys.shp,*** layer.

The trunk highways layer was subjected to Buffer operation:

1. From ArcToolbox Menu, click "Analysis", "Proximity", "Multiple Ring Buffer".
2. Locate and select the "Input Features" data layer - ***D4_AllHwys.sh***. Specify "Output Features", the layer to save to - ***D4_AllHwys_5Buff.shp***
3. Specify buffer "Distances" of 10,15,20,25 and 100 meters (32.8, 49.2, 65.6, 82 and 328.1 feet respectively). Click "Ok"

The trunk highways layer comprising 5 buffer-zones along the highways' polyline will be created. This will then be overlayed with polygon layer, ***D4_AllHwys_Hatch_Buffd_Int_Disso.shp.***

Intersection D4_AllHwys_Hatch_Buffd_Int_Disso.shp & D4_AllHwys_5Buff.sh:

1. From ArcToolbox Menu, click "Analysis", "Overlay", "Intersect".

2. Locate and select the “Input Features” – the two data layers - ***D4_AllHwys.shp*** and ***D4_AllHwys_Hatch_Buffd_Int_Disso.sh***. Specify “Output Feature” - the layer to save to ***D4_AllHwys_Hatch_5Buff_Int.shp***
3. Click “Ok”

The created layer will consist of 5 by 20 meter segments interspersed over all highways ROWs in the study area. However, there will be duplication of segments at given locations due to various reasons. Key among the reasons is Route Direction identifiers (D and I) on each trunk highway, hence having two segments at a location, one for each direction. To eliminate segment duplications,

1. From Toolbars click on “XTools Pro”
2. Select “Table Operations”, then “Add X, Y, Z Coordinates”. Deselect “Add Z-coordinate”, then click “Ok”

Apply “Dissolve” to this new data layer, D4_AllHwys_Hatch_5Buff_Int.shp

1. From ArcToolbox Menu, click “Data Management Tools”
2. Select “Generalization”, then “Dissolve”.
3. Input the “Input Features” data layer – ***D4_AllHwys_Hatch_5Buff_Int.shp***
4. Specify “Output Features” - ***D4_AllHwys_Hatch_5Buff_Int_Disso.shp***
5. Check all check boxes for “Fields to Dissolve by” – Distance, SegType, SegmID, X, and roadside (field distinguishing left-, right-, and median-sides of highways).
6. Click “Ok”

Overlay this data layer, ***D4_AllHwys_Hatch_5Buff_Int_Disso.shp***, with the Weeds data following ArcToolbox “Intersect” procedures. Save this to “Output Features” - ***D4_AllHwys_Hatch_5Buff_Weed_INT.shp***. Apply Dissolve on this layer following ArcToolbox dissolve procedures; dissolve by fields: Species, Distance, SegType, SegmID, X, Subdistrict, Ecozone, roadside (if created to distinguish between left-, right-, and median-sides of highways).
Save to D4_AllHwys_Hatch_5Buff_Weed_MILES_DISSO.shp

This data layer will be appropriate for determination of road-edge miles infested (see Figure 2). The selection of minimum fields to dissolve by eliminates segment duplications.

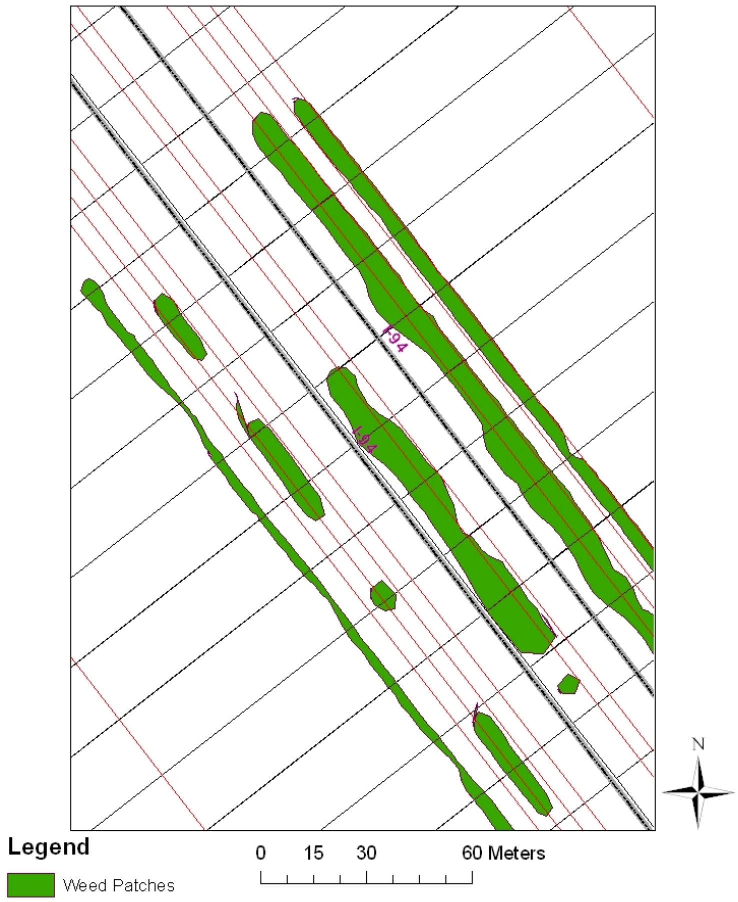


Figure C2: Illustration of segmentation of a divided highway (Interstate 94) right-of-way into 20m by 5m segments, and overlaying with weed infestation data.

Appendix D: Descriptions of Data Preparation and Analysis

Descriptions of Data Preparation and Analysis

Conduct data analysis following these procedures:

A. Prepare Data tables for evaluation of means by summing the acres infested (***acresxxx***) for each species per ECOLOGICAL ZONE. Obtain separate tables for qtr-mile and 3-mile segment as:

$$\overline{X} = \frac{\sum_{i=1}^{s} A_{si}}{L_{SEi}}$$

where $\overline{X}$ = the mean area infested by weed species in the ecological zone
s = is total number of segments selected for survey in ecological zone i
A_{si} = Total area (acres) infested in segment i
L_{SEi} = Total Linear miles surveyed in ecological zone (i)

Table D1: Sample - mean infested area per ecological zone evaluated from ¼-mile segments survey data, 2004.

Species	Ecological Zone	Total Area Infested (acres)	Surveyed Linear Miles	Mean (acres/L. mile)
Canada thistle	Hardwood	5.675	4	1.419
	Mn. Prairie	20.097	8.75	2.297
	..			
	..			
Leafy Spurge	Hardwood	0	4	0
	Mn. Prairie	0.085	8.75	0.010
	..			
	..			
Poison Ivy	Hardwood	0.547	4	0.137
	Mn. Prairie	0.081	8.75	0.009
	..			
	..			

B. Prepare Data tables for evaluation of Grand Means by summing "***acresxxx***" values for each species in District 4. The grand mean (for qtr-mile design) is obtained by summing the products of means and total linear miles for all ecological zones, then dividing the obtained value by the total Linear Miles in District 4. Sample obtained data is given in Table D1. The same results may be obtained by evaluating the sum of the products of means and weighting factors (ratio of total linear miles in an ecological zone and total linear miles in the study area) for ecological zones. The grand mean should be computed for all three weed species. For 3-milesampling design, the grand mean, for each species, is a simple mean, evaluated by dividing the total area (acres) infested the given species by total Linear Miles Surveyed in the entire District 4. Separate tables should be prepared for the qtr-mile and 3-mile sampling designs as (Table D1), following the formulae below:.

(i) Quarter-Mile Segments Survey

$$GM = \sum_{i=1}^{n} \overline{X}_i . \frac{L_{SEi}}{L_{EZi}}$$

where GM is the grand mean
n = total number of ecological zones in the study area
L_{SEi} = Total Linear miles of Mn/DOT managed roads surveyed in ecological zone i
L_{EZi} = Total Linear Miles of Mn/DOT managed roads in the ecological zone i

(ii) 3-Mile Segments Survey

$$GM = \frac{\sum_{i=1}^{n} A_i}{n}$$

where n is total linear miles surveyed
A_i = Total area (acres) infested in ecological zone, i

Table D2: Mean area and grand mean infested area per ecological zone evaluated from ¼-mile segments survey data, 2004.

Speicies	**Ecological Zone**	**Total Area Infested (acres)**	**Surveyed Area (Linear Miles)**	**Mean qtr-mi (acres/mile)**	**Grand Mean (acres/mile)**
Canada thistle	Hardwood	5.675	4.000	1.419	2.079
	Minnesota	20.097	8.500	2.364	
	Pine Moraines	0.878	3.250	0.270	
	Red River	22.931	8.750	2.621	
Leafy Spurge	Hardwood	0.000	4.000	0.000	0.005
	Minnesota	0.085	8.500	0.010	
	Pine Moraines	0.000	3.250	0.000	
	Red River	0.027	8.750	0.003	
Poison ivy	Hardwood	0.547	4.000	0.137	0.039
	Minnesota	0.081	8.500	0.010	
	Pine Moraines	0.265	3.250	0.082	
	Red River	0.000	8.750	0.000	

C. Prepare Data tables for evaluation of "Total Road Edge Miles" infested (T_I), miles:

$$T_I = \frac{N_{20m}.20}{1600}$$

where N_{20m} = Number of 65.6 feet (20 meter) segments in all sides-of-roads ROW (left, right, median) within ecological zone which are infested

Proportion Infested, P is:

$$P = \frac{T_I}{T}$$

where T is the total number of Road Edge miles surveyed in the ecological zone.

Obtain the TI and P values for each weed species under each SUBSECNAM category, and for qtr-mile and 3-mile surveys as:

Table D3: Example - Proportion of right-of-way infested as evaluated for ¼-mile segments survey data, 2004.

Species	Ecological Zone	No. 20m segments (N_{20m})	Total Road Edge Miles Infested (TI)	Total Road Edge Miles Surveyed	Proportion Infested (miles/mile)
Canada Thistle	Hardwood Hills	243	3.038	9.5	0.320
	Mn. Prairie	630	7.875	19.25	0.409
	..				
	..				
Leafy Spurge	Hardwood Hills	0	0.000	9.5	0.000
	Mn. Prairie	5	0.063	19.25	0.003
	..				
	..				
Poison Ivy v	Hardwood Hills	26	0.325	9.5	0.034
	Mn. Prairie	7	0.088	19.25	0.005
	..				
	..				

Prepare Data tables for evaluation of "Total Predicted Area Infested" in ecological Zones, Sub-districts, and entire District 4. Total area infested is obtained by multiplying Mean (acre/linear mile) for each region by Total Linear Miles in the region. Obtain separate tables for qtr-mile and 3-mile surveys as:

Table D4: Example – Total Predicted area infested in rights-of-way of ecological zones evaluated from ¼-mile segments survey data, 2004.

Species	Ecological Zone	Mean Infested (Acres/mile)	Total Miles in D4 (Linear Miles)	Total Infested (acres)
Canada thistle	Chippewa	1.419	350	496.650
	Hardwood	2.297	641	1472.377
	..			
	..			
Leafy Spurge	Chippewa	0	350	0
	Hardwood	0.010	641	6.410
	..			
	..			
Poison Ivy	Chippewa	0.137	350	47.95
	Hardwood	0.009	641	5.769
	..			
	..			

D. Prepare Data tables for evaluation of "Total Predicted Area Infested". Total area infested is obtained by multiplying Grand Mean (acre/linear mile) by the total Miles. Obtain separate tables for qtr-mile and 3-mile surveys as:

Table D5: Example – Total Predicted area infested in rights-of-way of District 4 evaluated from ¼-mile segments survey data, 2004.

Species	Grand Mean Infested (Acres/mile)	Total Miles in D4 (Linear Miles)	Total Infested (acres)
Canada thistle	2.052	1630	3344.760
Leafy spurge	0.005	1630	8.15
Poison ivy	0.039	1630	63.57

F. Prepare similar tables for SUBDISTRICTS category, and for both categories using the 2005 survey data.

Statistical Analysis: Evaluate means, standard deviation, and variance to characterize infestations; compare infestations and statistical differences across categories

Appendix E: LOGGING INSTRUCTIONS FOR TRIMBLE® PRO XR GPS

LOGGING INSTRUCTIONS FOR TRIMBLE® PRO XR GPS

The following descriptions are intended to guide the user of the Trimble® Pro XR GPS unit in recording spatial and attribute data .during field surveys. The document was compiled for in-house use of Mn/DOT (Mn/DOT, 2000). The document has been developed with the current problem at hand in mind: surveying for weed infested areas of the Mn/DOT's District 4. Although necessary details on us of this GPS unit in the surveying procedures have been included, in may be necessary for individual operators to modify steps or sequence of procedures to meet specific data collection requirements. Caution is recommended in adopting the procedures verbatim, which if not recognized, may result in errors in data recording and/or subsequent post processing.

Figure E1: Trimble® PRO XR GPS Unit used in the survey and data recording phases of the study.

Procedures for Operation of GPS in Survey and Data Collection

Check to make sure battery power in the hand held and back-pack are adequate. To change drained backpack unit batteries, replace one at a time. Carefully unclip the connector to the first battery, remove and replace it with a charged one. Close the clip firmly before changing the second one. NEVER DISCONNECT BOTH BATTERIES AT ONCE AS THE UNIT

MAY LOSE MEMORY SETTINGS.

1. Check cabling and batteries
2. Press the black power button at the top right of the logger to turn ON
3. Double click on *TerraSync* icon
4. Once you are outside, click on STATUS, SETUP, CONNECT TO GPS
5. Once the logger shows it has connected (will DING-DONG) and has a satellite connection and radio link, click on SETUP, DATA NEW (Fill in File Name), then Select Data Dictionary (GENERIC, etc.), click on CREATE
6. Wait for at least 4 satellites to appear before trying to log (< 4 won't log)
7. Click on OPTIONS and make sure REPEAT is √'d
8. Select type of feature you are to map (Highlight POINT, LINE, AREA). Be over your feature, or at its starting point before clicking CREATE
9. When you are ready to start logging, click CREATE (pen at top right will start counting positions)
10. Fill in the attributes while pen counts positions. You may want to click on PAUSE/LOG to suspend collection if type of feature is LINE or AREA to avoid too many points being collected at one position.
11. Once attributes are completed and there are at least 3-5 positions (for POINT data) counted click on OK, OK (in confirmation pop-up box). If LINE or AREA, proceed to walk the feature to be mapped. click on OK, OK (in confirmation pop-up box)
12. Repeat steps 8-11

Edit a Feature's Attributes

1. If you notice an error in the attributes you've entered, you can either CANCEL collection of the feature and do it over or ...
2. CLOSE the file (YES at confirmation pop-up box)
3. Click on NEW, EXISTING FILE
4. Locate the feature you want to edit and highlight it, click UPDATE, BEGIN
5. Make your changes and OK to finish
6. If you have more corrections to make, locate the feature to edit, highlight it, click BEGIN and make changes, OK to finish
7. If you are ready to continue logging new features, click UPDATE, COLLECT
8. Repeat steps 8-11 of Logging Instructions

THE BASIC STEPS WILL BE USED FOR NEARLY ALL APPLICATIONS (drainage, mowing, spraying, etc.) -THE TYPEOF FEATURE (point, line, area) TO BE COLLECTED, THE AMOUNT AND TYPE OF DATA REQUIRED ARE GENERALLY THE ONLY CHANGES YOU WILL ENCOUNTER.

To Use the Map Option

1. If you want to see where you have been (or broad-scale navigation with an existing file), click DATA, MAP
2. The symbols under MAP are defined as follows - activate by clicking on : The dark arrow is the SELECT TOOL (used to isolate a location on map);
The magnifying glass with the + is the ZOOM IN TOOL (use by drawing a small diagonal line over a feature {site} you want magnified);
The magnifying glass with the - is the ZOOM OUT TOOL (use same as above or just pecking at the feature {site} you want expanded);
The hand is the PAN TOOL (by clicking, HOLDING and dragging, you can move the map to where you want it);
The 'crosshairs' is the DIGITIZE TOOL
3. If you overshoot the feature {site} you want, you can start over by clicking on OPTIONS, ZOOM EXTENTS
4. To get back to collecting data, click on MAP, DATA, COLLECT

To Use the Navigate Option

1. To navigate directly to a feature (site), the target must be set in either MAP or DATA.
2. From MAP, identify the feature {site} and use the SELECT TOOL to grab it
3. (In either DATA or MAP) Click OPTIONS, SET NAV TARGET
4. Click MAP, NAV (Once into NAV, the screen will show DIRECT DIAL {a compass arrow} showing both HEADING and TURN {direction to go}, as well as a MESSAGE LINE and detailed INFORMATION LINES with distance, footage, direction, etc. By using these tools, you will eventually move to the CLOSE-UP SCREEN. This screen will have a BULL'S-EYE {target}, an X {current GPS location} and the MESSAGE LINE and detailed INFORMATION LINES with distance, footage, direction, etc. By following the directions, the X will be directly over the BULL'S-EYE and the INFORMATION LINES will read *VERY* close to, if not, "0 FEET/degrees".)
5. To change the target, click NAV, MAP or DATA, locate target from file, OPTIONS, SET NAV TARGET, then click MAP or DATA, NAV and follow navigation directions
6. To continue collecting data, click NAV, DATA, COLLECT

End of Day (Close File)

When you are done collecting data for the day, click CLOSE, OK to confirm, **X** out, OK to confirm (data is saved and stored automatically). This will bring you back to the desktop screen.
SETUP ->DISCONNECT GPS

Downloading Procedures

Once you are back at your office, follow the DOWNLOADING PROCEDURES

1. Connect the unit via serial port cable provided with the GPS unit. It will be a good idea to also connect the hand held unit to AC power to continue recharging batteries.
2. Locate program Active Sync which should already be loaded on your computer, and click it to open. This will establish connection between computer and GPS unit
3. Select FILE, CONNECT (will sound signal when connecting)
4. Locate GPS Pathfinder program loaded in your computer and click it on. Name PROJECT and Folders to receive data you will be downloading. OK.
5. From Menu bar, click on UTILITIES, DATA TRANSFER
6. Check to make sure top right corner icon show computer and GPS are connected.
7. Select GPS Running on Windows CE; RECEIVE, ADD DATA, DATA FILES (select from the list of files those you want to download – DEFAULT: All latest files which have not been downloaded will be highlighted in blue), TRANSFER ALL. OK.
8. Upon successful DATA TRANSFER, leave the data collector plugged in to charge, and also insert the backpack bag's extra batteries into the charger
9. Lightly press the power button once to put the logger to 'sleep'

COLD BOOT:
Every Monday morning before heading out, press and hold the power button until the screen goes black and an arrow and the word Trimble pop up on the screen. Let the logger reset until the desktop is restored before trying to open *Terrasync*. This procedure has been found to eliminate 'weird' error messages from disrupting data collection.

References

Mn/DOT, A.M. 2000. Login Instructions - Trimble® GPS (PRO XR), Mn/DOT, Alexandria, MN.