THE NEW INVASIVE *ODONTITES SEROTINA*: IMPACTS, RESPONSES AND PREDICTIVE MODEL

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Thesis Abstract

Invasive alien species (IAS) pose a serious threat to ecosystems and societies worldwide. Local ecological knowledge (LEK) is increasingly valued as a means of understanding environmental issues; however, its application in the context of IAS research has been limited. The overall objective of this study was to document the LEK of farmers and Weed Supervisors to gain insight into a recent IAS, *Odontites serotina*. I conducted semi-structured interviews with farmers and Weed Supervisors with *O. serotina* management experience. Results indicated that the socio-economic impacts for farmers were severe in affected rural communities. However, participants had developed promising control techniques, including the application of compost mulch. I used this LEK as well as data on species occurrence, environmental variables, and measures of propagule pressure to forecast the potential distribution of *O. serotina* across Manitoba. The risk map generated will be useful for guiding future monitoring and public outreach efforts.

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Table of Contents

List of Tables

List of Figures

List of Plates

Chapter 1: Introduction

Biological invasions have long been recognized as one of the greatest threats to biodiversity worldwide (Diamond 1989, Pimm *et al* 1995, Mack *et al* 2001). Vast regions of the earth have become completely dominated by invasive alien species (IAS), leading to a homogenization of biotic communities (Mooney and Cleland 2001, Lambdon *et al* 2008, Wright 2011). Impacts of biological invasions include species extinctions (D'Antonio and Vitousek 1992, Clavero and Garcia 2005, Wanless *et al* 2007, Sax and Gaines 2008, Clavero *et al* 2009), altered structure and functioning of ecosystems (Vitousek 1996, Gordon 1998, Kourtev *et al* 2002, Perrings *et al* 2005, Charles and Dukes 2007, Weidenhamer and Callaway 2010), as well as declines in land value and human health (Vitousek *et al* 1997, Horsch and Lewis 2009, Pejchar and Mooney 2009, Mack and Smith 2011). Furthermore, biological invasions interact with other agents of large scale change, such as climate change and soil nutrient cycling, in significant yet unpredictable ways (Dukes and Mooney 1999, Ehrenfeld and Scott 2001, Rodgers *et al* 2008, Dunham *et al* 2010).

Human activities are largely responsible for transporting species to novel environments (Perrings *et al* 2010) as well as creating conditions that facilitate their colonization of these new areas (Byers 2002, Buckley *et al* 2007, D'Andrea *et al* 2009). The economic consequences of IAS are severe; the estimated annual cost to the US economy is $120 billion, and agriculture, as one of the most adversely affected industries, has annual damages estimated at $26 billion (Pimentel 2009). Much of this expense is related to managing existing infestations, the cost of which increases exponentially once exotic species exhibit the rapid range expansion characteristic of most IAS (Mack *et al* 2000, Pimentel 2009). Therefore, early detection and rapid response (EDRR) is considered to be a crucial component of IAS management (Westbrooks 2004).

One essential component of EDRR involves indentifying areas that are at risk of future invasion in order to prioritize monitoring and management efforts (Byers *et al* 2002). Many studies in recent years have focused upon developing predictive models known either as ecological niche models, species distribution models, or habitat suitability models (Thuiller *et al* 2005, Ficetola *et al* 2007, Sato *et al* 2010). They usually relate species occurrence data to environmental variables in order to map potential IAS distributions. However, most of these studies have been conducted at large scales and considered only coarse variables such as climate (e.g. Peterson 2003, Thuiller *et al* 2005, Chen 2007). Although these models are useful, climate conditions alone may not always accurately predict limitations to plant distributions (Davis *et al* 1998, Peterson 2003, Welk 2004). Few studies have considered the influence of more localized environmental variables such as soil characteristics and hydrology (Rouget *et al* 2001, Rouget and Richardson 2003) or variables related to anthropogenic land use, which strongly influence the land's susceptibility to invasion (McNeely 2001). Even fewer have accounted for propagule pressure, the likelihood that an invasive species will be introduced to a given area (Guisan and Zimmerman 2000, Lockwood *et al* 2005), even though IAS are less likely to be limited by habitat requirements than by propagule availability (Rouget and Richardson 2003, Holle and Simberloff 2005).

Recently, there has been increased recognition of the value of documenting local ecological knowledge (LEK) to enhance understanding of, and respond to, a variety of ecological and socioeconomic problems (Brook and McLachlan 2005, Bart 2006). Given the anthropogenic connection to both the causes and the consequences of IAS and the lack of scientific data on many of these organisms, some have argued that LEK could be employed to address these gaps in information (McLachlan and Bazely 2003, Flora 2008). LEK builds upon the experiences, practical skills and even wisdom of lived experts who interact closely with and earn their livelihoods from the environment (Berkes 1999, McGregor 2000), including Indigenous people and farmers (Berkes *et al* 2003, Berkes 2005, Chalmers and Fabricius 2007, Mauro and McLachlan 2008). In so doing, LEK can enhance our understanding of local ecosystems, which is essential to invasion ecology (Levine and D'Antonio 1999, Mack *et al* 2001, Heger and Trepl 2003), and provide insights into IAS management (Bart 2010). By engaging community members in the research process, LEK also increases the likelihood that the research will provide outcomes that are meaningful to communities and more likely to translate into management action and changes in decision-making (Berkes 2005). Although the number of ecological studies incorporating LEK is increasing (Brook and McLachlan 2008), it has very rarely been used to understand species invasions (Bart 2010) and, to our knowledge, no habitat suitability models have yet incorporated the expertise of farmers or weed management professionals.

Odontites serotina (Red bartsia) is an IAS that is currently devastating pastures and haylands in Manitoba's Interlake region and has the potential to cause widespread damages across the Canadian Prairies. As a hemiparasitic plant, *O. serotina* forms opportunistic, parasitic relationships by establishing haustorial connections on the roots of host plants. Even a small population of hemiparasites within an ecological community can have significant impacts upon community structure and function (Press and Phoenix 2005). Associations with host plants, such as *Medicago sativa* (alfalfa), enable hemiparasites of the *Odontites* genus to grow larger with an increased resistance to herbivores, while also reducing host plant productivity and defenses against herbivores (Matthies 1995, Puustinen & Mutikainen 2001). Known to benefit from associations with a wide range of host species (Govier *et al* 1967), *O. serotina* thrives even during periods of drought (Snogerup 1982). It is also prolific, each individual plant is capable of producing up to 1400 seeds (MAFRI 2011), which further facilitates its ability to colonize established vegetation and to form dense monocultures.

Although *O. serotina* is technically controlled by cultivation and herbicide application (MAFRI 2011), these techniques are not feasible for most livestock and forage crop producers. Thus, it has tremendous impacts on farm families and rural communities. However, these impacts, and the mechanisms underlying its success in its invasive range, remain poorly understood.

Objectives

The overall goal of this research has been to understand and predict the distribution of a new invasive alien species (IAS) in central Manitoba and much of North America – *Odontites serotina* (Red bartsia)

The goal of Chapter 3 was to explore the role of local ecological knowledge in understanding the impacts of, and responses to, an IAS that is spreading across rural landscapes in North America. My more specific objectives were: (i) to determine socio-economic impacts of an IAS in farms and rural communities; (ii) to understand the ecological and anthropogenic factors that contribute to the spread of IAS; and, (iii) to identify cost-effective, environmentally sound management strategies for dealing with IAS. These topics were explored in relation to a case study of the IAS *O. serotina* in the Interlake region of Manitoba, Canada.

The goal of Chapter 4 was to gain insight into the combined role of local ecological knowledge and ecological data in understanding and predicting the spatial dynamics of *Odontites serotina*. In particular, our objectives were to (i) describe the factors that underlie its spatial distribution; (ii) predict future occurrences of this IAS by matching a habitat suitability model with measures of propagule pressure to assess the risk of *O. serotina* invasion across the region; and iii) more generally explore the role of local knowledge in informing socio-ecological modeling.

Chapter 2: Literature Review

2.1 Causes and Consequences of Invasive Alien Species

Invasive Alien Species (IAS) are defined as species established outside of their natural range that are capable of causing significant harm to the environment, economy or society (Environment Canada 2011). Although the distributional ranges of species fluctuate naturally, human activities have enabled species to cross long-standing biogeographic boundaries, such as oceans or mountain ranges, thus causing a dramatic acceleration in the rate at which species are transported around the globe (Mooney and Cleland 2001, Perrings *et al* 2005, Perrings *et al* 2010). While humans have been relocating species for thousands of years, at least since the commencement of agriculture (Low 2002), species migrations have increased by orders of magnitude in the past 500 years since the Age of Exploration, and especially in the past 200 years with the rise of global trade associated with the Industrial Revolution (Di Castri 1989, Hulme 2009). The global movement of species has now reached the point that the only terrestrial ecosystems that have remained largely unaffected by IAS are in Antarctica (Convey *et al* 2008), although even there, recent increases in human activity and climate change are increasing the probability of IAS establishment (Hughes and Worland 2010). Not surprisingly, wealthier countries with extensive international trade networks are most susceptible to new invasions (Levine and D'Antonio 2003, Westphal *et al* 2008, Pysek *et al* 2009, Perrings 2010). For example, in Canada 1229 (24.1%) of 5087 plant species that occur are exotic and 473 (9.2%) of these are considered to be invasive (CFIA 2008).

Not only are anthropogenic activities responsible for relocating species around the globe, they also contribute to the success of these species in their new locations (Burke and Grime 1996, Buckley *et al* 2007, D' Andrea *et al* 2009, Eschtruth and Battles 2009). Human-related disturbances, such as urban developments, paths, roads, fires, flooding events or tillage, which remove established vegetation, can facilitate the establishment of exotic species in recipient communities (Edward *et al* 2009) or allow them to become dominant in their new environments (Radford *et al* 2010). Anthropogenic climate change influences IAS, either by enhancing their ability to become established in some areas, exacerbating their impacts, or allowing established IAS to expand their geographic ranges, particularly at higher latitudes and altitudes (Luckman and Kavanagh 2000, Hellman *et al* 2008, Landhausser *et al* 2010).

It is difficult to quantify the societal and environmental impacts of biological invasions (Naylor 2000, Pimentel *et al* 2000, Colautti *et al* 2006). Some IAS are known to reduce crop yields (Pimentel *et al* 2005), reduce cultural and recreational values of land (Eiswerth *et al* 2005), negatively affect human health and wellbeing (Pejchar and Mooney 2009) and be expensive to control (Olson 2006). Dawson (2002) estimates annual damages from IAS in Canada to be $7.5 billion, however, the costs are likely even higher. The cost-benefit analyses commonly used to calculate the damages of invasions and the potential benefits of control strategies are generally anthropocentric and tend to disregard indirect use and the non-use values on natural ecosystems (Goulder and Kennedy 1997, Naylor 2000). Furthermore, there is no framework for assigning value to ecosystems (Colautti *et al* 2006). The difficulty in placing monetary values upon even the most innocuous extinct species, lost biodiversity, eco-system services or aesthetics, makes estimations of the cost of invasive species too low (Pimentel *et al* 2000, Pejchar and Mooney 2009). Despite the inherent difficulties in calculating the cost of biological invasions, it is clear that invasive species have an enormous economic impact (Pimentel *et al* 2000, Naylor 2000, Perrings *et al* 2005, Colautti *et al* 2006). However, studies investigating how IAS could be affecting other aspects of society, such as community relations and wellbeing, are not common.

Many have recognized the negative ecological consequences of the worldwide redistribution of species. Charles Elton was one of the first to identify IAS as a threat over 50 years ago, although the field of invasion ecology did not really blossom until the 1980s (Elton 1958, Simberloff 2011a). Many others now consider biological invasions to be one of the greatest threats to biodiversity worldwide (Hulme 2009, McGeoch *et al* 2010). There are numerous ways that IAS can alter the structure and disrupt the functioning of ecosystems. Some IAS have been found to influence ecosystem services such as the cycling of nutrients in the soil (Dassonville *et al* 2008, Castro-Dias *et al* 2009), to alter the frequency or intensity of fires (Brooks *et al* 2004, Keeley 2006, Pauchard *et al* 2008), and to affect hydrological flows (Zavaleta and Mooney 2000, Le Maitre *et al* 2002, Devine and Fei 2011). The IAS often outcompete native species for resources which can cause extirpations or local extinctions (Dillemuth and Cronin 2008, Sax and Gaines 2008, Hejda *et al* 2009). In the United States, it is estimated that 42% of endangered species are primarily at risk as a result of invasive species (Pimentel *et al* 2000). In Canada, invasive plants have been identified as threats to 44 species at risk

(CFIA 2008). Furthermore, invasion by one species in turn might facilitate the subsequent establishment of other exotic species, creating a so-called "invasional meltdown" (Simberloff and Von Holle 1999, Simberloff 2006, Nunez *et al* 2010). The IAS not only threaten biodiversity by placing threatened and endangered species at risk around the globe (Baillie *et al* 2004), but also contribute to the loss of beta diversity, which is the spatial variation or uniqueness among species assemblages, and are thus causing biotic homogenization (Wright 2011).

Although all IAS affect their new host ecosystems, some researchers posit that the risks posed are not always severe (Myers and Bazely 2003). Davis *et al* 2011 argue that it is a form of "biological bias" to favour native species over exotic species and, rather than place of origin, it is more important to consider a species' potential to harm biodiversity, human health or the economy. With some IAS, negative ecological effects have been limited to a decline in abundance of only one or a few native species (Bruno *et al* 2005), while in other cases, invasive species have actually been found to promote overall species richness and diversity (Sax 2002, Bruno *et al* 2004, Rodriguez 2006). Others argue that some IAS have become integral parts of their recipient biological communities, providing ecosystem services, such as habitat or resources, and some can also be economically beneficial (Ewel and Putz 2004). Therefore, it may not always be desirable to try to remove introduced species, especially given that IAS control efforts are often expensive and impractical (Davis *et al* 2011). Instead of trying to restore ecosystems to their historical state, some argue that those IAS which pose little threat to biodiversity, human health or the economy, should be embraced and incorporated into "novel ecosystems" (Hobbs *et al* 2009).

2.2 Invasion Ecology

Although each biological invasion has unique characteristics, all follow a common sequence (Richardson *et al* 2000, Mack *et al* 2000). Introduction, the first stage, usually occurs as the result of humans transporting species across major biogeographic obstacles. Although species are being introduced to new regions more rapidly then ever before, only a small percentage of introduced species become established in their new habitat (Williamson and Fitter 1996, Mack *et al* 2000). Highly adaptable introduced species that survive such pressures as predation, competition and adverse climates and have populations that are able to self-propagate in their new host environments are considered to be "naturalized" or "free-living exotics" (Westbrooks 2004). If a free-living, exotic species exhibits rapid growth within its new environment, it is considered an IAS (Mack *et al* 2000, Richardson *et al* 2000, Mooney and Cleland 2001). It is estimated that only 0.1% of imported species ultimately become IAS (Williamson and Fitter 1996).

Ecologists have long sought to understand the mechanisms which contribute to the success of those introduced species that ultimately become IAS; one factor that many agree plays an important role is propagule pressure (Reaser *et al* 2008, Edward *et al* 2009, Simberloff 2009a, Dullinger *et al* 2009, Huttanus *et al* 2011, Catford *et al* 2011). This is described as the number of propagules, the rate at which they are introduced and the spatial and temporal patterns of their arrival (Simberloff 2009a), and is related not only to the establishment of newly introduced species, but also to the range expansion of established

IAS (Lockwood *et al* 2005). A continued supply of propagules, particularly from a variety of sources, not only has demographic implications for IAS, but can also help them to evolve genetic adaptations to their new environment, increasing their chances of survival (Ficetola *et al* 2008, Da Silva *et al* 2010). Some have argued that propagule pressure is the most important factor in predicting the potential invasion success of species, as opposed to their invasive attributes or the characteristics of the recipient community (Colautti *et al* 2006, Lockwood *et al* 2007). However, a sufficient supply of propagules does not guarantee that a species will become established, particularly if the habitat is unsuitable (Simberloff 2009a). D'Antonio *et al* (2001) suggest that high propagule pressure is more likely to enable an introduced species to overcome biotic resistance to their invasion than intolerable abiotic conditions. Therefore, although propagule pressure is a contributing factor, it is also important to consider other factors that influence the success of invaders.

The Enemy Release Hypothesis is another possible explanation for the success of IAS (Elton 1958, Williamson 1996, Keane and Crawley 2002). Natural enemies, such as herbivores and pathogens, play an important role in regulating plant populations. Specialist enemies that control exotic plant populations in their native range are usually absent from recipient communities (Keane and Crawley 2002, DeWalt *et al* 2004). All plants within a biological community are attacked by generalist enemies; however, native species continue to experience pressure from specialist enemies, thus giving exotic species a competitive advantage in their new environment (Keane and Crawley 2002, Dewalt *et al* 2004, Liu and Stiling 2006).

Another complementary hypothesis used to explain the success of IAS is the Evolution of Improved Competitive Ability (EICA) (Blossey and Notzold 1995). Some researchers have found that IAS devote fewer resources to defending themselves against specialist herbivores or pathogens, and hence are able to select for genotypes to increase other fitness parameters such as biomass and reproductive capacity (Blossey and Notzold 1995, Joshi and Vrieling 2005). However, other research contradicts the EICA hypothesis. Willis *et al* (2000) found that IAS do not always grow larger in their introduced range, and when they do it is a plastic rather than genetic response. Moreover, other researchers have found that some IAS in fact grow smaller in their invasive ranges, which they attribute to IAS selecting for genotypes with increased resistance to generalist herbivores (Cripps *et al* 2009).

In turn, the Novel Weapons Hypothesis suggests that the secretion of allelopathic chemicals by some invasive plants may be used as a competitive mechanism in their introduced range (Bais *et al* 2003, Callaway and Ridenour 2004). All plant species secrete allelochemicals into the soil to defend against competitors or attract microbes (Bais *et al* 2003). In a plant's native environment these chemicals are relatively innocuous (Hierro *et al* 2005) because biological communities evolve as functionally organized units with intricate allelochemical relationships (Callaway and Aschehoug 2000). However, when introduced to a new biogeographic region, these same allelochemicals may be novel to the recipient community and detrimental to native plants, thus increasing the introduced species' invasive potential (Callaway and Aschehoug 2000, Bais *et al* 2003, Callaway and Ridenour 2004, Hierro *et al* 2005, Callaway *et al* 2008, Thorpe *et al* 2009).

Several researchers have attempted to identify attributes of species that are correlated with invasion potential (Rejmanek and Richardson 1996, Goodwin *et al* 1999, Kolar and Lodge 2001, Lake and Leishman 2004, Lloret *et al* 2005, Van Kleunen *et al* 2010). With respect to plants species, traits including small seed mass, time between seed crops (Rejmanek and Richardson 1996) and timing or duration of flowering period (Crawley *et al* 1996, Goodwin *et al* 1999, Cadotte and Lovett-Doust 2001, Pysek 2003, Lake and Leishman 2004, Lloret *et al* 2005, Cadotte *et al* 2006) are found to be correlated with high invasion potential. Van Kleunen *et al* (2010) conducted a meta-analysis of studies that compared the attributes of invasive plants to non-invasive plants and found that invasive plants had higher growth rates, and measures of fitness such as seed production. Interestingly, Lloret *et al* (2005) found that how an exotic plant's traits interact with the recipient community is more important than the actual attributes themselves. If an exotic plant's attributes are rare within the recipient community, for example, if it flowers at a different time than native plants in the same community, it will have less competition for pollinators, and thus a greater chance of proliferating and becoming invasive (Lloret *et al* 2005). These findings support the Empty Niche Hypothesis, which refers to the possibility that certain exotics may be successful because they access resources with are not utilized by other species within the community (Elton 1958, Mack *et al* 2000).

Determining whether or not a free-living exotic will eventually become an IAS is confounded by lag phases (Kowarik *et al* 1995, Sakai *et al* 2001, Crooks 2005). Although Williamson and Fitter (1996) posit that only a small fraction of free living exotics will eventually exhibit the rapid population growth associated with IAS, lag times in range expansions of free-living, exotic species can render risk assessments inaccurate (Simberloff 2009). Populations of exotic species can remain low for several decades while evolutionary or other changes occur which allow them to adapt to the new environment or to develop new invasive genetic traits to facilitate the colonization process (Sakai *et al* 2001, Crooks 2005). This occurs with most exotic species, with the average lag phase being five decades. However, there is great variability, and the lag time tends to be lower with unintentionally introduced species (Larkin 2011). Multiple introductions often contribute to an exotic species' ability to eventually overcome lag phases, as increased genetic diversity can lead to a greater capacity to evolve attributes that facilitate invasion (Sakai *et al* 2001). Given the uncertainty caused by lag phases, diligence and adherence to the precautionary principle are encouraged when managing any exotic species (Crooks 2005, Larkin 2011).

Much research has also focused on identifying the characteristics of biological communities which influence their susceptibility to invasion (Elton 1958, Burke and Grime 1996, Levine and D'Antonio 1999, Dukes 2002, Heger and Trepl 2003, Brown and Peet 2003, Gilbert and Lechowicz 2005). One of the earliest invasion ecologists, Charles Elton (1958), suggested there was a correlation between biological diversity within a biological community and its vulnerability to invasion. More recent studies have tested and supported Elton's theory, finding that more diverse communities have fewer unused resources available for potential colonizing species and hence are less likely to be invaded (Tilman 1997, Knops *et al* 1999, Dukes 2002). However, others have found that either the diversity of a community has no influence on its invasibility (Eschtruth and Battles 2009), or the same conditions, such as moisture or nutrients, that promote native species diversity might indeed facilitate invasions (Robinson *et al* 1995, Palmer and Maurer 1997, Stohlgren *et al* 1999, Spence *et al* 2011). Belote *et al* (2008) found that diverse communities were more susceptible to invasion than species-poor communities following disturbance. One explanation for these contradictory outcomes is related to scale: a negative correlation between native species diversity and community invasibility can exist at a small scale, while a positive correlation might exist at a large scale within the same ecosystem (Levine 2000). Another study, by Davies *et al* (2007) found that scale does not always explain what they term the "diversity-invasibility paradox". They offer site productivity as an alternative explanation; sites with high productivity exhibit a negative correlation between diversity and invasibility whereas sites with low productivity tend to exhibit a positive correlation (Davies *et al* 2007).

Another theory suggests that, instead of diversity or productivity, it is fluctuation in resource availability within biological communities that makes them vulnerable to invasion (Davis *et al* 2000, Colautti *et al* 2006). Resource availability often fluctuates within a biological community; extant vegetation can be destroyed as a result of various disturbances, resulting in a decline in nutrient and water uptake; supply of resources can increase as a result of excess precipitation, eutrophication or increased light due to an opening in forest canopy. Davis *et al* (2000) hypothesize that it is during these fluctuations, when there is an excess of resources available to colonizing species, that communities are most vulnerable to invasion. Recent studies have supported this theory, as increased snowfall has been found to facilitate invasion in mixed-grass prairie communities (Blumenthal *et al* 2008) and invasive annual grasses have also been found to establish more readily during resource pulses in which additional nutrients or water were added to the system (James *et al* 2006).

2.3 Invasive Species Management

Considering the potential negative ecological and socio-economic consequences of IAS, it is not surprising that land managers and policy makers are taking action. Management of IAS encompasses a wide range of activities from developing legislation and strategic policies, to monitoring for potential new threats, to disseminating practical advice on species identification and control methods, to ground-level control activities (Myers and Bazely 2003). For land managers, there are a wide variety of options for combating IAS, including: biological control agents; chemical treatments; and mechanical or physical removal (DiTomaso 2000, Myers and Bazely 2003).

Biological control agents can be cost-effective and, in some cases, may provide the most effective response to IAS infestations (Meyer and Fourdrigniez 2010). Among plants, the greatest successes have been achieved controlling cacti and species that reproduce asexually rather than sexually (Chaboudez and Sheppard 1995). However, biological control programs tend to be expensive, involve many years of research and a great deal of uncertainty, and have the potential to negatively affect non-target native species (McFadyen 1998, Strong and Pemberton 2000, Muller-Scharer *et al* 2004, Messing and Wright 2006, Paynter *et al* 2008, Simberloff 2011b). They are also frequently unsuccessful, with only about 20-30% of biological control agents proving to be effective (McFadyen 1998, Fowler *et al* 2000, Sheppard *et al* 2003). Temperate annual plants have proved to be particularly resistant to biological control (Chaboudez and Sheppard 1995), in part because seed predators are usually not effective control agents since most plants are not seed limited (Myers and Risely 1999, Turnbull *et al* 2000). However, considerable variability in the success of biological control programs and a lack of clear relationships between plant biology and potential for successful biological control, make it difficult to generalize among species (Charudattan 2005). Therefore, McFadyen *et al* (2000) warn against classifying certain types of plants as being unsuitable targets for biological control for fear of discouraging potentially successful biological control programs

In turn, some argue that chemicals are essential to weed management (Sigg 1998). Westbrooks (2004) argues that chemicals eventually break down in the environment, whereas, if left untreated, IAS cause ever-increasing problems. Herbicide application is ubiquitous, with about 25% of rangelands in the United States being treated with these chemicals (Bussan and Dyer 1999). However, even a single application of herbicide has the potential to damage non-target species including desirable plants species, soil microbes, birds, amphibians, humans and other mammals (Rinella *et al* 2009, Zarnetske *et al* 2010, Yi *et al* 2011). Therefore, land managers often consider herbicides as a last resort when combating IAS, to be employed only when all other measures have failed (Tu *et al* 2001).

The timing of herbicide application, which varies depending upon both the target species and the type of chemical, is closely related to its success (DiTomaso 2000). To minimize impacts on non-target species, various innovative herbicide application techniques have been developed, including wicks, hack and squirt, and injection (Tu *et al* 2001). However, chemicals seldom provide long-term control of IAS unless combined with other management strategies (Bussan and Dyer 1999, Blackshaw *et al* 2008, Sellers and Ferrell 2010).

Mechanical and physical removal techniques, these including the mowing, cutting or hand-pulling of plants, are advocated as the most environmentally friendly weed management strategies (Hobbs and Humphries 1995). There is minimal impact upon non-target species and, relative to herbicide application, manual removal has been found to better enhance the productivity and native diversity of biological communities following control efforts (Flory and Clay 2009). However, it is important to consider the biology of the invasive plant, and worthwhile to carry out some experiments to evaluate these control methods before adopting them at a large scale, as they can become counter-productive if not properly implemented (Tu *et al* 2001, Myers and Bazely 2003). Hand-plucking is effective as a means of controlling annual, biennial and tap-rooted perennial weeds (Hanson 1996). Woody species can also be controlled with this method, but only if care is taken in removing all root fragments (Jager and Kowarik 2010). However, with some perennial invasive plants with deep or easily broken roots, like leafy spurge (*Euphorbia esula*), this action can actually facilitate spread (Hanson and Rudd 1933). Cutting or mowing can also be an effective way to control many plant species, but the timing is important (Tu *et al*

2001, DiTomaso *et al* 2010). Generally, it is most effective to mow or cut plants before they flower and set seed (Hanson 1996). However, some species, such as yellow starthistle (*Centaurea solstitialis*) respond to early cutting with vigorous re-growth and seed production, and are best controlled by mowing if it is timed to coincide with the onset of flowering (Benefield *et al* 1999).

One criticism of manual and mechanical removal of IAS is that due to the labour-intensiveness of these techniques, they are usually only applicable when IAS have infested only small areas or when the cover of IAS is low (Hobbes and Humphries 1995). Pulling even flimsy weeds can be physically strenuous and time consuming (Tu *et al* 2001). However, innovative land managers have found ways of overcoming labour shortages to successfully implement manual IAS removal projects. Simberloff (2009b) outlines several projects where convict labour was used to successfully eradicate IAS in the United States. School children have also been involved in many manual IAS removal projects in North America (e.g. Lagerquist 2007, Thompson 2010). Worldwide, many IAS eradication efforts, including those detailed in the Proceeding of the International Conference on Eradication of Island Invasives (Veitch and Clout 2002), have depended heavily upon the efforts of volunteer labour. Involving volunteers in manual IAS removal projects in national parks in the USA has been not only successful and cost-effective for the parks service, but has also represented an important opportunity to educate and involve communities in ecological restoration (Akerson 2008). This interaction between scientists and volunteers is a form of citizen science, an increasingly popular way to broaden the scope of ecological research, which enables the public to make meaningful contributions to data collection (Cohn 2008, Delaney *et al* 2008, Silvertown 2009).

Manual and mechanical removal of IAS are most effective when used in conjunction with other management strategies such as chemical control (Simberloff 2009b). Indeed, experts frequently advocate integrating multiple approaches when dealing with IAS (Hobbs and Humphries 1995, Buckley *et al* 2007, DiTomaso *et al* 2010, Sellers and Ferrell 2010). Integrated Weed Management (IWM) involves the use of several complementary control measures, such as herbicide/mechanical control, or biological/herbicide control, and often produces better results than adopting any one method in isolation (Buckley *et al* 2007, Simberloff 2009b, DiTomaso *et al* 2010). However, some also hypothesize that when multiple approaches are combined they are enhanced by synergistic interactions. For example, hand-pulling weeds may help to provide soil conditions that are more suitable for fungi used in biological control; similarly, foliar re-growth after cutting or mowing may be more nutritient-rich and thus benefit insects such as weevils used for biological control of plants (Hatcher and Melander 2003).

For IAS management programs to be successful at large scales, coordinated efforts are required because stakeholders who ignore IAS infestations allow their lands to act as a source of invader propagules and thereby contribute to increased impacts and increased control costs for others (Epanchin-Neill *et al* 2009). However, collective action is difficult to organize when many different stakeholders are involved (Epanchin-Neill *et al* 2009, Klepeis *et al* 2009). Thus, there is an opportunity for governments and environmental non-governement organizations (ENGOs) to play a strategic role in coordinating these efforts. Recently, policy makers have begun to respond to the increasing threat posed by IAS by developing national action plans, such as the Invasive Alien Species Strategy (IASS) in Canada (IASS 2004), and the National Invasive Species Management Plan (NISMP 2008) in the US. Cooperative human networks, including the Invasive Species Council of Manitoba, have developed to help stakeholders adopt a collaborative approach to the prevention and management of IAS (ISCM 2011). These groups also focus upon IAS monitoring and public education, which are essential components of early detection and rapid response (EDRR) (Westbrooks 2004). This EDRR is critical to any management effort, because management costs increase dramatically once species begin to exhibit the rapid population growth associated with IAS (Mack *et al* 2000, Pimentel 2009, Kaiser and Burnett 2010). Improving communication and cooperation between sub-national groups such as the ISCM could have significant implications for EDRR and the global fight against IAS (Simpson *et al* 2009).

2.4 Predictive Modeling

With the increasing emphasis upon EDRR in management strategies (Leung *et al* 2004, Westbrooks 2004, Simberloff 2009b), many studies in recent years have focused upon developing predictive models known alternatively as ecological niche models, species distribution models or habitat suitability models (e.g. Thuiller *et al* 2005, Ficetola *et al* 2008, Sato *et al* 2010). These predictive models are crucial for prioritizing EDRR monitoring and management efforts because they identify areas at risk of future invasion (Byers *et al* 2002). To develop these models, species occurrence data are usually related to environmental variables in order to map potential invasive species distributions. However, most have been at large scales and emphasized coarse variables such as climate (e.g. Peterson 2003, Thuiller *et al* 2005, Chen *et al* 2007) that may not always accurately predict limitations in plant distributions (Davis *et al* 1998, Peterson 2003, Welk 2004). Therefore, it is useful to consider other important mechanisms of species invasions, including the biology of the invading species and interactions between biotic and abiotic factors (Richardson *et al* 2004, Thuiller *et al* 2005). Most predictive modeling studies have not considered the influence of more localized environmental variables such as soil characteristics and hydrology (Rouget *et al* 2001, Rouget and Richardson 2003), and few have accounted for variables related to anthropogenic land use which also strongly influence susceptibility of ecosystems to invasion, especially in human-dominated environments (McNeely 2001).

Although it is important to identify areas at risk of IAS establishment through habitat suitability models, these species are less likely to be limited by habitat requirements than by propagule availability (Rouget and Richardson 2003, Holle and Simberloff 2005). Therefore, habitat suitability models alone are not sufficient to assess the risk of invasion. Few studies modeling the potential distribution of IAS have accounted for the role of propagule pressure in the invasion process (Guisan and Zimmerman 2000, Lockwood *et al* 2005). By measuring distance to invasion foci, or source populations, Rouget and Richardson (2003) incorporated propagule pressure into an invasive plant distribution model. Herborg *et al* (2007) used introduction effort, specifically the amount of ballast water released at various ports in the USA, as a measure of propagule pressure which they matched with habitat suitability to estimate the risk of the *Eriocheir sinensis* (Chinese mitten crab) establishment. To forecast the potential distribution of *Didemnum vexillum* (colonial tunicate) along the coast of British Columbia, Herborg *et al* (2009) combined an ecological niche model with five transport vectors associated with its spread. These studies highlight the importance of combining measures of propagule pressure with habitat suitability models to achieve overall risk evaluations for IAS that can help to guide EDRR monitoring programs.

2.5 Local Ecological Knowledge

Accepting that IAS are generally recent phenomena, that they often represent a significant threat to extant ecosystems, and that little scientific data exist for many of these organisms, some have argued that LEK might be used to address these gaps in scientific research (McLachlan and Bazely 2003, Flora 2008). Local ecological knowledge (LEK) is based upon people's observations related to direct interactions with their environment accumulated over a lifetime (Anadon *et al* 2009). The LEK involves a mix of observations and monitoring (Shava *et al* 2010), and is more than a means of understanding the stories behind the statistics, but rather an important source of region-specific ecological and socio-economic information (Hood *et al* 2009). There has been increased recognition of the value of documenting LEK to enhance understanding and respond to a variety of ecological and socioeconomic problems (Brook and McLachlan 2005, Bart 2006).

Complex environmental changes, such as biological invasions, often have human causes and consequences. Furthermore, they often occur at speeds and scales too great to be understood by conventional ecological research alone (Tesh 2000, Moller *et al* 2004). In most cases, insufficient baseline data on pre-invasion, extant biological community structure or nutrient cycles limit insights regarding the ecological dynamics of the invasion process (Parker *et al* 1999). By building upon the experiences, practical skills and wisdom of lived experts who continue to earn their livelihoods from ecosystem services (Berkes 1999, McGregor 2000), LEK can contribute to understanding local ecosystems, which is essential to understanding biological invasions (Levine and D'Antonio 1999, Mack *et al* 2000 Heger and Trepl 2003, Hood *et al* 2009).

LEK is particularly valuable in cases where participants' livelihoods are directly linked to ecosystem services, thus it often involves Indigenous people (Berkes *et al* 2003, Berkes 2005) but can also involve farmers (Chalmers and Fabricius 2007, Mauro and McLachlan 2008). It is fitting that in Europe farmers are not only considered to be food producers, but are also officially recognized as environmental stewards (Pacini *et al* 2004). Farmer experimentation has led to numerous innovations over the years and some argue that formal research needs to be more open to farmers' informal experimentation (Hoffmann *et al* 2007, Milestad *et al* 2010). Ostensibly, researchers have recognized that the LEK of farmers can be applied to IAS management (Bart 2010). However, its application in the field of invasive ecology has been extremely limited.

Not all scientists have been enthusiastic about incorporating LEK into scientific studies. One criticism put forth is that many studies documenting LEK do not clearly describe the participant selection process or explain why the participants qualify as experts in the field (Davis and Wagner 2003). In Davis and Wagner's view, a lack of transparency in the participant selection process calls the credibility of LEK research into question. Another issue with LEK is that participants usually have a limited capacity to understand processes occurring at coarser spatial scales (Gadgil *et al* 2003, Chalmers and Fabricus 2007). Others have suggested that its use to assess the risk of IAS can be problematic, because it leaves the process open to subjectivity and motivational bias (Paini *et al* 2010) and in many cases is not supported by complementary scientific studies (Gilchrist *et al* 2005).

In contrast, other researchers have advocated integrating LEK with traditional ecological science methods, as these different approaches can augment each other to provide a more holistic understanding of complex environmental issues (Moller *et al* 2004, Brook and McLachlan 2008, Ballard *et al* 2008). Paini *et al* (2010) found that using ecological modeling to complement LEK enabled them to obtain more complete risk assessments for IAS.

The documentation of LEK also encourages discussion between scientists and the communities in which they conduct, and that are affected by, their research (Turner *et al* 2000). Community members often feel distanced from science, including invasion ecology, and base their management decisions instead on tradition, emotion or personal values (McPherson 2004). Top-down approaches that do not allow community input result in communities that are unmotivated about land management activities or that are hostile to government outreach (Selman 2004). Engaging community members in the research process, provides a voice to community members who are often otherwise marginalized by environmental and resource management decision-making processes (Brook and McLachlan 2005) and increases the likelihood that the research will provide outcomes that are both meaningful and beneficial to affected communities (Berkes 2005). Encouraging the exchange of information between scientists and communities increases the credibility of management plans, and in turn the potential that they will translate into effective management action (Ballard *et al* 2008, Epanchin-Neill *et al* 2009) . In this way, scientist-community partnerships can contribute to biosecurity, social well-being (Flora 2008), and making social-ecological systems more resilient in the face of radical changes such as species invasions (Shava *et al* 2010).

2.6 Hemiparasite Biology

About 1% of terrestrial plants (over 3000 species) are parasitic angiosperms (Phoenix and Press 2005), which occur in a wide variety of natural vegetation communities worldwide (Marvier 1998). The majority of these, nearly 2000 species, are root hemiparasites found within the Orobanchaceae family (Phoenix and Press 2005). These species contain chlorophyll, which enables them to survive autotrophically, however, they have the potential to form opportunistic, parasitic relationships by establishing connections on the roots of host plants known as haustoria (Smith 2000). These connections enable hemiparasites to draw resources, such as water, carbon and nutrients from host species (Govier *et al* 1967, Snogerup 1982). Hemiparasitic Orobanchaceae have exceptionally high evapotranspiration rates, sometimes an order of magnitude higher than that of their host species (Phoenix and Press 2005). This enhances carbon gain from hosts, and also prevents hemi-parasites from over-heating in warm climates (Press *et al* 1989).

Hemiparasites are partially autotrophic; hence they must compete with their hosts and non-host species for light. At sites with high vegetation biomass, competition for light may outweigh the benefits of parasitism, thus enabling fully autotrophic plants to outcompete hemiparasites (Pennings and Callaway 2002). Some have suggested that this can limit hemiparasites' distribution to relatively nutrient-poor, low-biomass habitats where competition for light is minimal (Matthies 1995, Smith 2000).

Host-parasite interactions can affect the productivity and fitness of both the hemiparasite and the host plant (Matthies 1995, Matthies 1996). Without a host, hemiparasites generally exhibit poor growth, but when attached to a host, their productivity and reproductive capacity has been observed to increase by as much as 40 times (Matthies 1997). Typically, increased growth in hemiparasites is positively correlated with the severity of damage to the host species (Matthies 1996). However, effects upon hosts can also be greater than the amount of resources removed by hemiparasites, partially due to their high transpiration rates (Press *et al* 1989), but also as a result of parasite-induced physiological responses in hosts that can result in altered resource allocation and abnormal growth (Pennings and Callaway 2002). Parasitized host plants may also become more susceptible to drought (Press *et al* 1987) and herbivores (Alder 2000). Given this disproportionate impact on host species, hemiparasites are also known to reduce overall productivity of biological communities (Matthies 1996, Frost *et al* 1997, Joshi *et al* 2000). For example, *Rhinanthus spp.* (rattle), have been found to lower the overall productivity of grasslands by 8-73% (Davies *et al* 1997).

Many hemiparasites are generalists; some are known to parasitize hundreds of different host species (Musselman and Press 1995). However, species' vulnerability to parasitic attack varies, and associations with certain hosts can be more beneficial to hemiparasites than others (Marvier 1998). Nitrogen-rich hosts such as legumes are often assumed to be the best hosts, as host nitrogen supply has been linked to increased autotrophic carbon acquisition in hemiparasites (Matthies 1996). However, others have suggested that simultaneously parasitizing multiple hosts of different species, for example both legumes and graminoids, allows hemiparasites to acquire a greater balance of resources and thus provides the greatest benefit to growth and reproduction (Govier *et al* 1967).

Due to variable effects upon host species, hemiparasites have the ability to alter inter-specific competition within biological communities, particularly between host and non-host species (Matthies 1996, Joshi *et al* 2000, Pennings and Callaway 2002). Given hemiparasites' tremendous evapotranspiration rates, heavy infestations could also affect overall soil moisture, which could affect both host and non-host species (Sala *et al* 2001). Furthermore some hemiparasites have been found to facilitate the establishment of other exotic species (Joshi *et al* 2000). Hemiparasites have also been found to alter nutrient cycles. Hemiparasites' foliage is known to have higher concentrations of nutrients than other species, and since they often occur in nutrient poor environments their leaf litter can result in a considerable increase in available nutrients, which favours those species most able to access these nutrients (Quested *et al* 2002, Press and Phoenix 2005). Given the significant impacts that even a small population of hemiparasites can have upon community structure and function, some consider them to be keystone species within ecological communities (Press and Phoenix 2005).

Given their potential to negatively affect both host species and biological communities, it is not surprising that some hemiparasites have become IAS. Two of the most problematic invasive hemiparasites are species of the *Striga* (witchweed) genus. Both *S. asiatica and S. hermonthica,* are serious agricultural weeds that parasitize graminoid crop species such as *Zea mays* (corn), *Pennisetum glaucum* (pearl millet) *Saccharum spp.* (sugar cane) and *Sorghum bicolor* (sorghum) (Sand *et al* 1990). *S. asiatica* was a considerable threat in the southern United States, first identified in the region in 1956 and infesting 177, 000 hectares of cropland by the early 1960s, until an aggressive eradication program reduced its extent to 6,000 ha as of 1999 (Westrbooks and Eplee 1999). *S. hermonthica* continues to be one of the most damaging agricultural weeds in Africa, causing more than a billion dollars in lost crop yields annually (Haskins and Oliver 2011). It causes considerable damage to host plants and has proven difficult to control given its prolific seed production and the fact that these seeds remain viable for many years in the soil (Lendzemo *et al* 2009). It negatively affects tens of millions of sub-Saharan African farmers, who produce a wide range of subsistence cereal crops, particularly in areas with low fertility soils where herbicide is not a feasible control option (Ransom 2000).

2.7 *Odontites serotina* (Red bartsia)

Odontites serotina (Red bartsia) (Scoggan 1957) is an IAS that is currently devastating pastures and haylands in Manitoba's Interlake region (Plate 2.1). It is a herbaceous plant, from the Orobanchaceae family, growing up to 50cm in height, with stalkless, undivided, lanceolate, toothed leaves, and pinkish-red, hermaphrodite flowers occurring in terminal spikes (Plate 2.2) (Fitzgerald *et al* 2011). Adapted to a wide range of climate conditions, the distribution of *O. serotina* in its native range extends throughout most of Europe from Scandinavia to Portugal, Greece and Turkey (Marhold 2011). It has also been recorded in six states in northeastern USA and nine of the ten Canadian provinces (USDA 2011) and is considered a prohibited noxious weed in Alberta (AIPC 2011) and a noxious weed in Manitoba (MAFRI 2011). It was first recorded in Manitoba at the Gimli military airbase in 1954 (Scoggan 1957), and has been reported in 19 rural municipalities (RMs) across the province (ISCM 2009).

A generalist hemiparasite known to benefit from associations with a wide range of hosts including graminoid, legume and forb species (Govier *et al* 1967), *O. serotina* is known to thrive even during periods of drought (Snogerup 1982). As a prolific seed producer, each individual is capable of producing up to 1400 seeds (MAFRI 2011), which are known to remain dormant in the seed bank for many years. One report indicated that 26% of seeds remained viable after being in the soil for 11 years (Meleshko 1988). This facilitates its colonization of established vegetation, and formation of dense monocultures (Plate 2.3). *O. serotina* is technically controlled by cultivation and herbicide application (MAFRI

2011); however, these techniques are not feasible for most livestock and forage crop producers (Paulson pers. com.)

2.8 Study Area

We conducted this study in the Interlake Region, which is situated in south-central Manitoba between Lake Manitoba and Lake Winnipeg. This area is located within the Interlake Prairie ecoregion, a transition zone marking the southern limit of closed Boreal Forest and the northern extent of open arable agricultural land (Smith *et al* 1998). Native vegetative cover in the area is predominantly aspen hardwood and aspen mixedwood forest, and low-lying areas are covered with sedges and willows (Smith *et al* 1998). The region also contains some rare vegetation community types including tall-grass prairie and alvar-like vegetation communities (Hamel and Foster 2004, Manitoba Conservation Data Centre 2011). About 40% of the Interlake region is farmland, of which 25% is forage crop or pasture and of which 15% is annual crop (Manitoba Conservation 2002). The main crops are *Medicago satvia* (alfalfa) and alfalfa mixtures, tame hay/other fodder, *Brassica napus* (canola) and *Avena sativa* (oats) (Statistics Canada 2006). Livestock production focuses largely on cattle and hogs (Statistics Canada 2006).

Soils of the region are Dark Gray Chernozems overlying dolomites and limestone of the Red River Formation. Extensive calcareous, loamy, stony till deposits in the region are interspersed with stone-free clay till with little slope (0-2%). Due to poor drainage and soil characteristics, cultivated crops are generally difficult to establish in this region (Podolsky 1986). The climate is continental, with a mean annual temperature of 1.8ºC;

the mean minimum in January is -18.7 ºC, and mean maximum in July is 18.9 ºC (Environment Canada 2008). The average annual precipitation is 526.4 mm per year, of which 409 mm falls as rain (Environment Canada 2008).

We divided our study region in two (Figure 2.1). The first represented the region in which *O. serotina* was initially established in the province. This invasive plant was first identified in Manitoba at the Gimli airport in 1954 (Scoggan 1957) and was first reported in the RM of Armstrong in the 1960s (Paulson, pers. comm.). We used this as our main study area, both for collecting species occurrence data and environmental variables to develop our predictive model, and for conducting interviews with farmers that had a long history of managing this IAS. After a lag period, *O. serotina* has recently begun to spread rapidly to neighbouring regions. We sampled two recently invaded areas in the RM of Bifrost and the RM of Siglunes to evaluate the effectiveness of our model (model evaluation area).

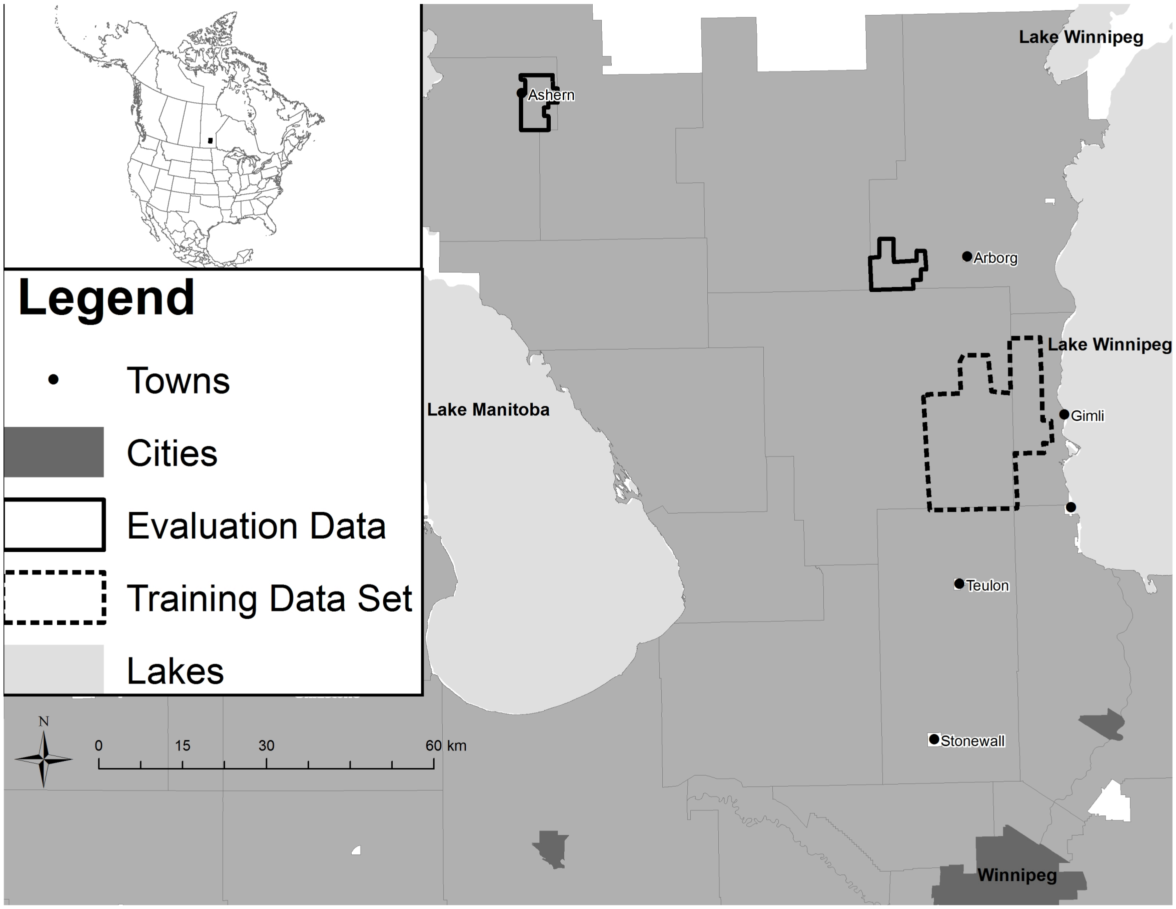

Figure 2.1: Study area with training data set and evaluation data set indicated.

Plate 2.2: *O. serotina* choking out competition and devastating forage crops

Plate 2.3: *O. serotina* close-up

Plate 2.4: *O. serotina* forming a monoculture in fields

Plate 2.5: Roadside infestation *O. serotina*

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Chapter 3: Applying Local Ecological Knowledge to Enhance Understanding of Biological Invasions: a case study of *Odontites serotina* in Manitoba, Canada.

3.1 Abstract

Invasive alien species (IAS) have had devastating impacts on the biodiversity and functioning of ecosystems around the globe; yet, there is little insight into the socio-economic implications of these species even in human-dominated landscapes. We explored the role of local ecological knowledge (LEK) in understanding the implications of IAS for rural landscapes in North America. Our specific objectives were: to determine environmental and socio-economic impacts of an IAS on farms and in rural communities; to understand the ecological and anthropogenic factors that contribute to the spread of IAS; and to identify cost-effective, environmentally-sound management strategies for dealing with IAS. We explored these topics in relation to a case study of the IAS, Red bartsia (*Odontites serotina),* in the Interlake region of Manitoba, Canada. *Odonities serotina* is an invasive hemiparasitic plant that has been spreading in forage and pasturelands across central Manitoba since its introduction in the 1950s. We interviewed farmers and Weed Supervisors to document the causes, consequences and control of *O. serotina*. We found that the IAS had substantial adverse consequences to farmers and Weed Supervisors, both regarding the costs and time associated with control measures and lost productivity of the land. It also had negative implications for personal and community wellbeing. It was associated with marginal land and anthropogenic disturbances, and dispersal was linked to water movement and the transportation of forage crops. Farmers experimented with a wide diversity of management techniques, including herbicide treatment, manual removal, mechanical removal, vector management and nutrient management. Of these, the application of compost mulches seemed to be particularly effective. Our results highlighted the value of LEK for better understanding and managing IAS, especially in human-dominated landscapes. The knowledge of these lived experts provided insights that could not have been attained through conventional ecological research, and merits further exploration in the IAS literature.

KEYWORDS:

agriculture-dominated landscapes; hemiparasitic plant; local ecological knowledge; local farmer knowledge; invasive alien species; invasive species management; pastures and forage; socio-economic impacts

3.2 Introduction

Biological invasions have long been recognized as one of the greatest threats to biodiversity worldwide (Diamond 1989, Pimm *et al* 1995, Mack *et al* 2000). Impacts of biological invasions include species extinctions (Clavero and Garcia 2005, Wanless *et al* 2007, Sax and Gaines 2008, Clavero *et al* 2009), altered structure and functioning of ecosystems (Vitousek *et al* 1996, Gordon 1998, Kourtev *et al* 2002, Perrings *et al* 2005, Charles and Dukes 2007, Weidenhamer and Callaway 2010), and declines in land value and human health (Vitousek *et al* 1997, Horsch and Lewis 2009, Pejchar and Mooney 2009, Mack and Smith 2011). Agriculture is one of the industries most adversely affected by invasive alien species (IAS) (Pimentel *et al* 2000*,* Mooney 2005, Colautti *et al* 2006). In the United States, annual economic losses to forage crops by inedible, invasive plants approximate $1 billion and farmers spend about $5 billion each year to control invasive plants in pasture and rangelands (Pimentel *et al* 2000). In Canada, the cost of invasive species to farmers is also considerable, exceeding hundreds of millions of dollars each year (IASS 2004).

Control of invasive species can encompass a wide range of activities from developing legislation and strategic policies, to disseminating practical advice on a variety of control methods, to ground-level control activities (Myers and Bazely 2003). Recently, IAS have received more attention from policy makers, and national action plans have been developed, such as the Invasive Alien Species Strategy (IASS 2004) in Canada and the National Invasive Species Management Plan (NISMP 2008) in the US. Networks, including the Invasive Species Council of Manitoba (ISCM 2011), focus upon public education, outreach that involves farmers in rural landscapes, and IAS monitoring. Both are essential components of early detection and rapid response (EDRR) (Westbrooks 2004), which is critical to any management effort, as the cost of management can be enormous once a species becomes established (Mack *et al* 2000).

For farmers and other stakeholders, IAS management options include mechanical, physical, biological, or chemical control (DiTomaso 2000, Myers and Bazely 2003). Biological control agents can be cost-effective and, in some cases, provide the only effective response to invasive species (Meyer and Fourdrigniez 2010). However, these programs can also be expensive, require many years of underlying research, involve a great deal of uncertainty and may also adversely affect desirable native species (McFayden 1998, Strong and Pemberton 2000, Muller-Scharer *et al* 2004, Messing and Wright 2006, Simberloff 2011).

They are also frequently unsuccessful (Fowler *et al* 2000, Sheppard *et al* 2003). Temperate annual plants have proved particularly resistant to biological control (Chaboudez and Sheppard 1995), in part because seed predators are often not effective control agents (Myers and Bazely 2003). Others argue that chemical control is essential to weed management (Sigg 1998). Ubiquitous in approach, about 25% of rangelands in the United States are treated with herbicides (Bussan and Dyer 1999). However, chemical control also has the potential to damage non-target species (Rinella *et al* 2009) and seldom provides long-term control of IAS unless combined with other management strategies (Blackshaw *et al* 2008, Sellers and Ferrell 2010). Mechanical or physical removal, in the form of cutting or pulling plants, is advocated as the most environmental-friendly weed management strategy (Hobbs and Humphries 1995). Both can be effective, particularly when used in conjunction with other management strategies such as chemical control (Simberloff 2009); indeed, experts frequently advocate integrating multiple approaches when dealing with IAS (e.g. DiTomaso 2000, Buckley *et al* 2007, Sellers and Ferrell 2010).

IAS are inextricably linked to human activity. Impacts of IAS upon biological communities have been widely studied (e.g. Lodge 1993, Mack and D'Antonio 1998, Hejda *et al* 2009, Meffin *et al* 2010) and many studies have examined the characteristics of ecosystems that make them susceptible to biological invasions (e.g. Lonsdale 1999, Rejmanek 2005, Bulleri *et al* 2008, Kreyling *et al* 2008). Yet, much less is known about the role of humans and rural communities in facilitating invasion. Human-focused studies generally focus on economic impacts (e.g. Pimental *et al* 2000, Shwiff *et al* 2010) without considering other socio-cultural factors.

Hence most research considering IAS (e.g. Lonsdale *et al* 1995, Taylor and Hastings 2004, Williams and Grosholz 2008) is science-based and driven by experts. Directly including stakeholders in the research process is important, not only because they often have insights into innovative IAS management approaches (Anaya 1999, Bart 2010), but also to help ensure pragmatic outcomes.

There is increasing recognition of the value of local ecological knowledge (LEK) for understanding and responding to socioeconomic and even biological problems (Bart 2006, Brook and McLachlan 2008). Complex, human-induced environmental changes, such as biological invasions, have human causes and consequences. Furthermore, they often occur at speeds and scales too great to be understood by conventional ecological research alone (Tesh 2000). In most cases, pre-invasion states of ecosystems are obscured by insufficient baseline data on extant biological community structure (Parker *et al* 1999). By building upon the experiences, practical skills and wisdom of lived experts who reside in and earn their livelihoods from the environment (Berkes 1999, McGregor 2000), LEK can contribute to understanding local ecosystems, and help clarify the processes underlying biological invasions (Levine and D'Antonio 1999, Mack *et al* 2000, Heger and Trepl 2003). Importantly, the incorporation of LEK encourages communication between scientists and the communities that are affected by the research (Turner *et al* 2000) and can provide a voice to stakeholders who are often otherwise marginalized by environmental and resource management decision-making processes (Brook and McLachlan 2005).

The aim of this research was to explore the role of LEK in understanding the impacts and responses to an IAS that is spreading across rural landscapes in North America. My more specific objectives were: to determine environmental and socio-economic impacts of an IAS in farms and rural communities; to understand the ecological and anthropogenic factors that contribute to the spread of IAS; and to identify cost-effective, environmentally sound management strategies for dealing with IAS. We explore these topics in relation to a case study of the IAS *Odontites serotina* in the Interlake region of Manitoba, Canada.

3.3 Study Area and Methods

The Invasive *Odontites serotina* (Red bartsia)

Odontites serotina (Red bartsia) is an IAS that is currently devastating pastures and haylands in Manitoba's Interlake region with the potential to cause widespread damages across the Prairies. Introduced from Europe, *O. serotina* is a hemiparasite, and thus forms opportunistic, parasitic relationships by establishing haustorial connections on the roots of host plants. Hemiparasites are keystone species and even a small population within an ecological community can have significant impacts upon community structure and function (Phoenix and Press 2005, Press and Phoenix 2005). Associations with host plants, such as *Medicago sativa* (alfalfa), enable hemiparasites of the *Odontites* genus to grow larger with an increased resistance to herbivores, while also reducing host plants' productivity and defenses against herbivores (Matthies 1995, Adler 2000, Puustinen & Mutikainen 2001). Known to benefit from associations with a wide range of host species (Govier *et al* 1967), *O. serotina* thrives even during periods of drought (Snogerup 1982). It is also prolific; one plant can produce up to 1400 seeds (Manitoba Agriculture Food and

Rural Initiatives (MAFRI) 2011) that can remain dormant in the seedbank for over 11 years (Meleshko 1988), which further facilitates its colonization of established vegetation and formation of dense monocultures.

Study Area

Situated in the Eastern Interlake Region, the Rural Municipalities (RM) of Armstrong and Gimli have been the most seriously impacted by *O. serotina.* This invasive plant was first identified in the Gimli area in 1954 (Scoggan 1957) and was reported in the RM of Armstrong in the 1960s. The region is predominately agricultural, and more than half of the landbase is used for farming. The main crops are alfalfa (*Medicago satvia*) and alfalfa mixtures, tame hay/other fodder, canola and oats (Statistics Canada 2006). Livestock production focuses largely on cattle and hogs, with some cultivation of sheep, goats, and bison (Statistics Canada 2006). Soils of the region are Dark Gray Chernozems overlying dolomites and limestone of the Red River Formation. Extensive calcareous, loamy, stony till deposits in the region are interspersed with stone-free clay till with little slope (0-2%). Due to poor drainage and soil characteristics, cultivated crops are often difficult to establish in this area (Podolsky 1986). The climate of the region is continental, with a mean annual temperature of 1.8ºC; the mean minimum in January (-18.7 ºC) and mean maximum July (18.9 ºC); the average annual precipitation is 526.4 mm per year, of which 409 mm falls as rain (Environment Canada 2011).

Participants

We present findings from interviews with farmers and Weed Supervisors who have many years of experience managing IAS. In total, 20 farmers and five Weed Supervisors were interviewed for this research. Interviews were conducted until a saturation point was reached and no new information was being introduced (Berg 2001). One criticism of studies that incorporate LEK is that they lack transparency regarding how participants are selected, and what qualifies them to be considered experts in the field (Davis and Wagner 2003). Although their properties had varying levels of *O. serotina* infestation, all the landowners who participated in this study had at least 10 years experience managing this invasive on their land. Initial landowner participant screening was based on maps of current and historical infestations of *O. serotina*, and landowners having the longest history of managing this species were contacted first. From these initial calls 16 of the participants were selected. The other farmers who participated in the study also had extensive management experience and were recommended as knowledgeable by their peers. The remaining participants were Weed Supervisors, employed by rural municipalities to control noxious weeds on public property and to enforce the province of Manitoba's Noxious Weed Act (Manitoba Weed Supervisors Association 2011). All those who participated have extensive training in IAS and weed management, and those who participated in this study have been managing *O. serotina* in their Weed Districts for at least 15 years.

Three of the landowners were agricultural producers from the RM of Gimli. The remaining 17 landowners were from the RM of Armstrong; 12 were still actively farming; four were retired and were leasing their land; one worked full-time off the farm and also rented out his land. Among the 15 landowners who still actively farmed, 12 worked full or part-time off the farm. The ages of participants ranged from 36-79 years of age, with an average age of 54. Four of the farmers were female; the other 16 and all five Weed Supervisors. The latter all work in the five Manitoba Weed Control Districts in which *O. serotina* has been reported: Interlake, Rockwood/Rosser, Selkirk, Cameron/Glenwood/Sifton and Beasejour/Lac du Bonnet.

Interview Procedure and Data Analysis

Prior to beginning interviews, all questions and methodologies were subject to an ethics review by the Joint Faculty Human Subject Research Ethics Board Protocol at the University of Manitoba. This review ensured that the project met all ethical guidelines. It was granted approval under project number (#J2007:018).

Semi-structured interviews (Bernard 2000) were conducted to collect LEK regarding *O. serotina,* and each was approximately 60-90 minutes in duration. The benefit of the semi-structured interview approach was that it provided flexibility to explore participants' answers in greater depth and permitted participant observations and concerns to inform the direction of the research. This was important, as the goal of this and similar LEK-focused research is to allow participants to contribute to the research in a meaningful way and to ensure the research outcomes benefit the local community (Berkes 2005). Interview topics included participant observations regarding *O. serotina's* impacts, mechanisms underlying its success in the region, and management responses. The interviews were audio recorded and transcribed verbatim. Transcriptions were imported into the program Atlas.ti (Muhr 1997), where they were reviewed and coded thematically (Berg 2001) and later consolidated into the broader themes that inform the research presented here.

3.4 Results and Discussion

3.4.1 Impacts

Economic Impacts

All farmers cited reduced productivity of their land as a consequence of *O. serotina* invasion. The worst affected farmers saw a drastic decline in the productivity of infested lands,

> *"In the fields where it is really thick, I lose more than half of my crop. I get probably less than 25% of the former yield in those areas, if that."* - Larry Nosaty, farmer

This had serious economic consequences; the average estimated annual cost of lost productivity was $8915.70 ± $2292.81 (mean ± SE) among those farmers reporting (n= 20). With pastures incapable of sustaining the same numbers of cattle, farmers either needed to lower stocking rates or purchased hay to supplement animal diets. For other producers, a lower yield of hay meant less forage to sell, resulting in a direct cause of working off-farm. It has also become increasingly difficult for local producers to sell hay.

As word of *O. serotina* spread, producers noticed that buyers were becoming more selective about purchases of hay coming from the region. According to Weed Supervisor, George Willis, "*it is harder to sell the second cut of hay. Most people have to consume it on their own farms, so it affects their income* "

Lower productivity was not the only economic consequence of *O. serotina* invasion. Some farmers and Weed Supervisors also invested considerable resources into controlling infestations. Weed Supervisor, Fred Paulson explained that, "*your whole farming operation has to change if you want to manage it. Your costs go up, your methods change*." Certainly, many farmers with serious infestations spent much time on management,

> *"I spend at least a couple of weeks controlling it each year, so that would be at least 120 hours. I don't really know how to put a cash value on that!"*
> Larry Nosaty

Considerable monetary investment was also required to purchase equipment or herbicides required as part of a management strategy, for farmers (n=20) this annual expenditure averaged $2152.63 ± $538.37 (mean ± SE). This had serious implications for farmers or Weed Supervisors with already tight operating budgets. The Weed Supervisor in the most affected region describes the costs involved with *O. serotina* management,

> *"About 70-75% of our budget goes into Red bartsia now, that's probably about $75,000-80,000 going towards controlling RB. Our budgets haven't*

> *increased, so it means that we have had to sacrifice other things."* - Fred Paulson

Many participants felt that the government, at the federal level in particular, should play a larger role in mitigation efforts because the original introduction occurred on a military airbase.

Social Impacts

Many of the impacts of the invasion by *O. serotina* were social and cultural in nature. Some farmers believed the issue was not taken seriously beyond the immediate area, and suggested that provincial and federal authorities had failed to recognize the severity of *O. serotina's* impacts upon producers. A few speculated that this could have been related to the fact that the area is predominantly cattle country, with lower land values and, in turn, lower tax rates. Thus, little attention and few resources have been devoted to finding affordable *O. serotina* mitigation strategies.

One producer, John Hudyma, was discriminated against when he was denied service simply because he resided in the area most affected by this IAS. The seed store in the nearby town of Arborg refused to repair his tractor for fear of seed contamination. For others, the threat of *O. serotina* even limits their potential for social interactions,

> *"We know one farmer who is so afraid of getting it on his property that if he knows you have it on your property he won't even come over to your place, because he doesn't want to walk anywhere near it for fear he will carry it home with him."* - Marion Jansen, farmer

In addition, there was a wide diversity of indirect impacts. Many farmers already had time management pressures balancing farm work with off-farm employment. Additional hours spent on IAS management averaged 112.11 ± 32.29 (mean ± SE) annually among participating farmers (n=20), which contributed to less relaxation time, less time with families and fewer opportunities to volunteer and spend time in the community. Although IAS are just one contributing factor, high levels of stress among farmers are linked to a number of health and safety risks. These include mental health issues (Gregoire 2002, Carruth and Logan 2002, Fraser *et al 2005*), marital problems (Carruth and Logan 2002) and work place injury (Kidd *et al* 1996). Additionally, those who used chemicals as part of their management strategy faced health risks associated with exposure to herbicides (Pimentel *et al* 1992, Alavanja *et al* 2003, Engel *et al* 2005).

Rather than uniting people around a common cause at the community level, IAS became a source of tension among neighbours. Many participants complained that infestations on their land were a result of source populations on neighbouring properties. Others recognized the futility in attempting to control *O. serotina* when neighbours were not equally vigilant,

> *"If your neighbor doesn't do anything, you don't stand a chance. We have been spraying it, but our neighbours haven't, so we're fighting a losing battle."* - John Kozera, farmer

Some also noticed reluctance among producers to discuss this problem, or potential solutions, among their peers.

> "*Actually, most people we talk to in our area don't really want to talk about it. Nobody wants to talk about this horrible weed*." - Marion Jansen

Unwillingness to discuss this issue undermined effective communication and education regarding the IAS, especially since much of the rural population was aged and had poor access to the Internet.

> *"Instead of via the Internet, many get their information from neighbours. I think word of mouth is the most common method that information travels among farmers*." - Glen Nicoll, farmer

3.4.2 Mechanisms of Invasion

Ecological Processes

Participants associated certain microhabitat and climate conditions with infestations. Soils lacking in nutrients were commonly regarded as being most prone to invasion, due to an absence of competing vegetation.

> *"The major factor is lack of competition, so any area where you have a lack of competition, usually here that is in the higher spots because sulfur and nitrogen are mobile.*" Glen Nicoll

Conversely, nutrient-rich areas, including yard sites where livestock are fed during the winter, promoted the growth of desirable species and were less likely to become infested.

> "*Our pasture here has quite a bit of manure on it and I think that slows the Red bartsia down quite a bit. I have only got it along the fences now, where the cattle don't graze as much."* -Joseph Cherniak, farmer

These observations are consistent with research that suggests that hemiparasitic plants thrive in nutrient- poor environments (Matthies 1995, Joshi *et al* 2000). Because hemiparasites rely on photosynthesis to produce carbon, habitats with fewer plants to compete with for sunlight could be advantageous.

Extreme weather events, such as droughts and floods, have been linked to the invasibility of biological communities and in turn the increased abundance of exotic species (Kreyling *et al* 2008, Jimenez *et al* 2011). Several participants attributed annual fluctuations in *O. serotina's* abundance on a landscape scale to variations in weather and particularly soil moisture,

> *"Last year was a really bad year, because it was dry. Every field from Silver to Komarno was just purple."* John Kozera, farmer

Indeed, hemiparasites of the *Odontites* genus are successful even during periods of drought (Snogerup 1982). Much academic discussion has focused upon the potential effects of climate change upon the future success of invasive species. While it is difficult to generalize, because much depends upon individual species life histories and there is considerable variation in future climate projections, some believe that climate change will favour invasive species (Dukes and Mooney 1999, Kreyling *et al* 2008, Jimenez *et al* 2011). Should climate change result in drier conditions, particularly increased periods of drought, *O. serotina* infestations could become more severe in the future.

Given the slow pace of spread since its introduction, a few participants, particularly Weed Supervisors from outside the most seriously affected region, were not convinced that *O. serotina* would become a widespread problem,

> *"I don't think it will happen that quickly, like some other invasive species, not when I think of how far it has spread in the past 50 years. In 50 years it has spread only 40 miles. In the next 10 years… I just see it moving further west."* George Willis.

The MAFRI (2011) factsheet also dismissed *O. serotina* as a rather localized issue. This reflected the opinion of some participants that the issue was not taken seriously beyond the immediately affected area. However, relative to many other exotic species that have become harmful IAS in Canada, *O. serotina*'*s* introduction to Manitoba is quite recent (CFIA 2008). It is problematic to assume that *O. serotina* will continue to spread slowly, in light of the fact that most exotic species experience lag phases before changes to their environment, or genetic adaptations, enable them to rapidly expand their range (Sakai *et al* 2001, Crooks 2005). Lag phases vary in duration, but the average is five decades (Larkin 2011), roughly equal to the time *O. serotina* has been established in Manitoba (Scoggan 1957). Multiple introductions often occur before circumstances or attributes emerge that enable invasion (Sakai *et al* 2001). According to participants, at least two separate introductions of *O. serotina* occurred, both at military airbases in the Interlake region, one near Gimli the other near Winnipeg Beach. Due to the uncertainty caused by lag phases, some studies advocate that the precautionary principle inform responses to any exotic species (Crooks 2005, Larkin 2011). The majority of participants were of the opinion that *O. serotina* had accelerated range expansion in recent years, evidenced by their observations at a landscape scale, suggesting that it may have already overcome its lag phase.

Although most common in human-altered landscapes, some have observed *O. serotina* in natural habitats:

> *"When I was moose hunting North of Riverton I noticed it up there and that is wild country up there, no agriculture. It only needs a little bit of an opening and it will grow."* John Kozera

O. serotina has been identified either within, or in close proximity to several Provincial Parks and Wildlife Management Areas, mostly within the Interlake region (Figure 3.1).

Continued spread into natural habitats, particularly grasslands or alvar-like vegetation communities, could have negative consequences. Research on other invasive hemiparasites has demonstrated that they have the potential to reduce productivity, influence competitive interactions between other species within biological communities and facilitate the establishment of other exotic species (Mathies 1996, Joshi *et al* 2001, Press and Phoenix 2005). *O. serotina* is a threat to native species that are suitable hosts, has the potential to displace endemic species that fill a similar ecological niche and influence interspecific competition within recipient communities.

> *"Red bartsia is very competitive, so it will eventually move into natural areas. You probably won't find solid mats of it growing in grasslands like you would in a hayfield or a pasture, because the competition is a lot stronger and it won't move as quickly without the disturbance of being grazed or cut. Red bartsia is going to be something that is present, putting additional pressure on the systems, but I don't think it will completely obliterate them the way something like Leafy Spurge might."* -Fred Paulson

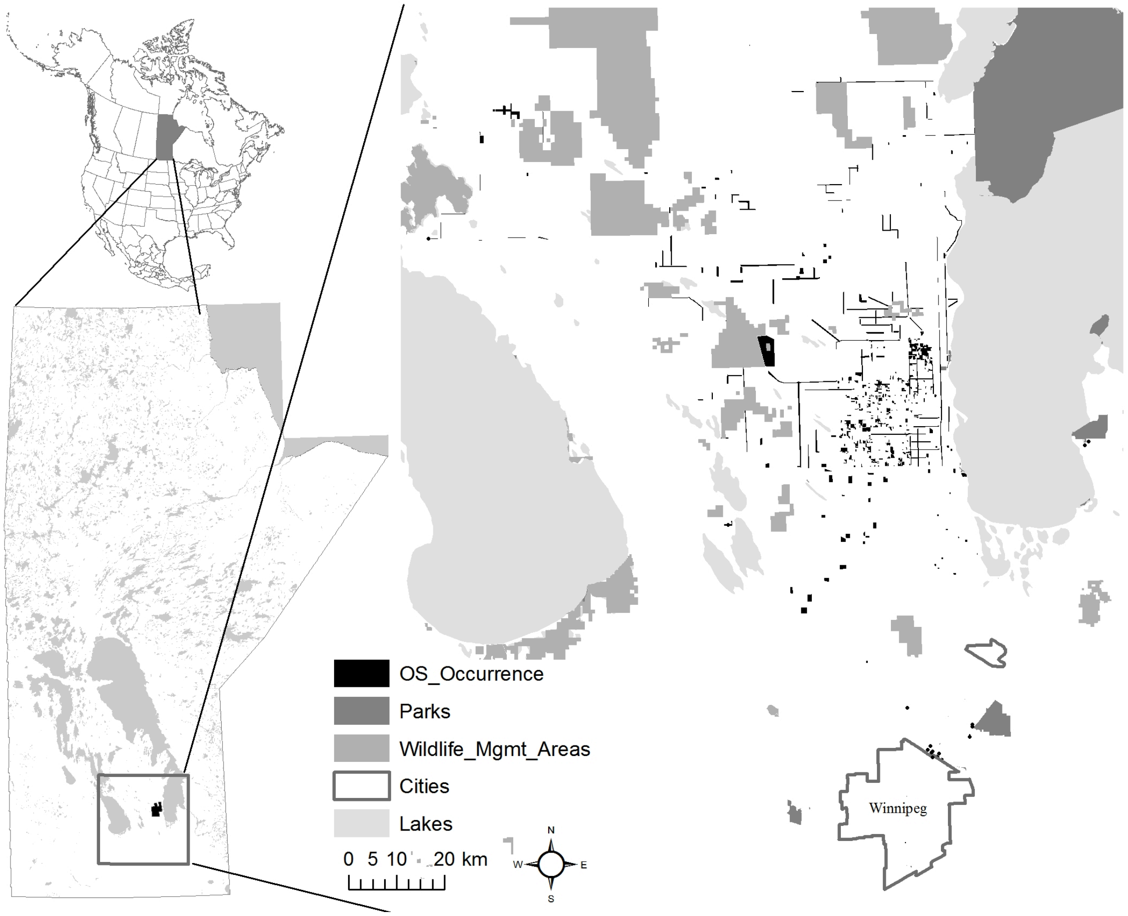

Figure 3.1: *O. serotina* distribution in relation to natural areas in Manitoba's Interlake Region

Anthropogenic Factors

Participants also observed possible connections between some characteristics of local rural communities and the success of *O. serotina*. One demographic trend in local communities recognized as a potential contributing factor to *O. serotina*'s range expansion was the aging rural population. The average age of farmers in the worst affected region was 53 years of age and only 7.5% of farmers in the area were under the age of 35 (Statistics Canada 2006).

> *"A lot of people around here are retired or they are just renting out the land, so nobody wants to do anything about Red bartsia."* – John Kozera

The increased proportion of land that is being rented rather than owned by the farmers who work it (Figure 3.2) was also seen as problematic in the context of IAS. One retired farmer noted that renters had less vested interest in the long-term health of the property, and therefore were less likely to put effort into expensive, or labour-intensive, management strategies.

> "*The neighbour, who is leasing my land now, is not going to go out there and pull it by hand, and with Red bartsia unless you go out there and pull it by hand it seems like nothing hurts it."* - Daniel Klyzub, retired farmer

Other farmers admitted they were less inclined to devote time and effort to combating *O. serotina* on land they were renting. Furthermore, leasers were less likely to know the full management history of land they were renting, and thus less aware of areas that were prone to invasion. Because farmers have spread their operations across larger areas rather than farming contiguous blocks of land, the distance farm equipment travels across the landscape has increased. Farm equipment was identified as one of the primary dispersal vectors for *O. serotina* and other IAS, thus the increase in land rental was correlated with increased propagule pressure.

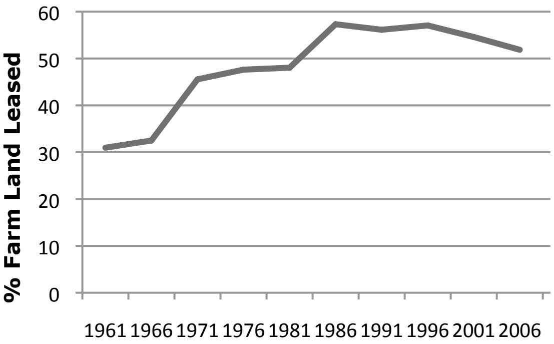

Figure 3.2: Agricultural Land Leased in the RM of Armstrong (Statistics Canada 2006)

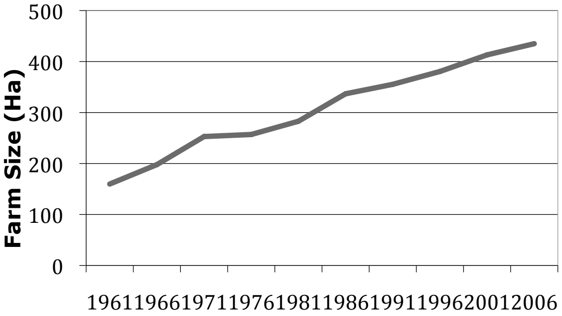

Figure 3.3: Average Farm Size in the RM of Armstrong (Statistics Canada 2006)

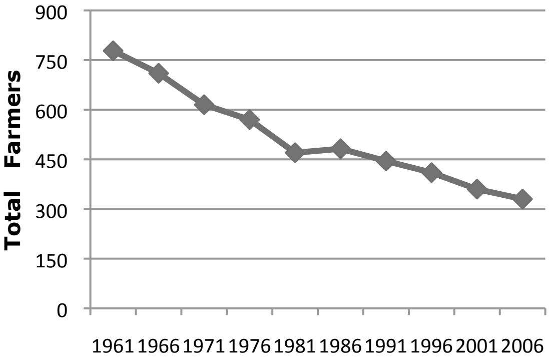

Figure 3.4: Total Farmers in the RM of Armstrong (Statistics Canada 2006)

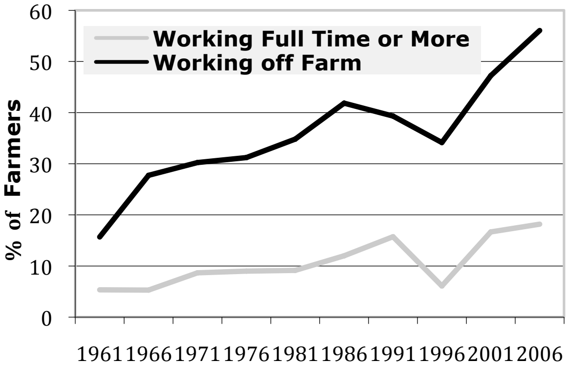

Figure 3.5: Farmers in the RM of Armstrong working off farm (Statistics Canada 2006)

Rural depopulation is another phenomenon that could have implications for IAS management. Fewer people now operate larger farms (Figures 3.3 & 3.4), undermining one of the more important components of any IAS management strategy, EDRR (Westbrooks 2004). When a farmer has more land to manage, it is improbable that infestations will be noticed, mapped out, and quickly managed.

> "*There is a new generation of farmers coming along now, but they have been forced to be a lot bigger. Where a farmer used to farm one section,*

> *now he farms five sections. So as far as them paying attention to the details, they are not likely going to.* " -George Willis

Yet this did not always seem to be true. Using sophisticated equipment, including GIS technology to manage his lands, one of the larger scale producers in this study did not have a problem with *O. serotina* infestations. However, his large forage and annual crop operation was different than most of the farms in the region that were restricted to pastures and haylands.

> "*On a pasture with a lot of trees you'll find Red bartsia along the side of the bushes and maybe landowners don't even know it is there. You don't run over pastureland very often, so you often don't know all your weed problems. If you have a quarter with bush and meadows, you may not notice you have Red bartsia for quite a while."* - Glen Hnatiuk, Weed Supervisor

Another demographic shift that may have implications for IAS is the increasing number of producers that work off-farm, which has increased in recent decades (Figure 3.5). Labour intensive activities, including invasive species management, might be neglected simply because there is insufficient time.

> "*People aren't taking precautions, like cleaning their equipment before moving between fields. Yeah, it would help if they started, but in order to get all the seed off so you don't spread it anywhere, you'd probably need a*

> *good two hours. It comes down to time and money. Guys are working and they have five hours after work to do their farming. They aren't going to spend a couple of hours, or any more money, to wash their equipment."* - Les Becker, farmer

Dispersal Vectors

Natural Vectors

As an annual plant, *O. serotina* relies on seed dispersal to expand its range. Abiotic causes such as hydrochory (water) and anemochory (wind) will disperse *O. serotina* seeds. Although wind could transport its tiny seeds short distances, water was the most commonly cited natural dispersal vector. Weeds are often hydrochorous species, particularly if their seeds are buoyant (Boedeltje *et al* 2004*)*, and are successful in areas that are submerged for at least part of the year (Benvenuti 2007). Some suggested that animals may also act as dispersal vectors,

> *"Birds or deer carry it also, because I've noticed it in the bush and I'm sure that livestock haven't been in there."* - John Kozera

Because animals generally do not graze *O. serotina* (MAFRI 2011), seed transport is likely caused by epizoochory, adhesion to animals' hooves or fur, rather than endozoochory, through animal's digestive system, as reflected by the coarse hairs on the seeds, which facilitate adhesion (MAFRI 2011).

Anthropogenic Vectors

Long distance *O. serotina* dispersal is almost exclusively caused by anthropochory. Altering natural hydrological flow, through the creation of drainage ditches and culverts, can facilitate the movement of invasive species (Stromberg *et al* 2007). Because water is a dispersal vector, when the rate of flow is increased, it accelerates the spread of IAS and can lead to their eventual invasion of agricultural fields (Benvenuti 2007). Several participants noted a correlation between the construction of a drainage ditch or culvert on, or adjacent to, their property and the establishment of *O. serotina.* Prior to these alterations to the hydrological regime, they either had no *O. serotina* on their property or small patches that they had been able to contain through handpicking. After drainage ditches were constructed, enabling water to flow more rapidly from neighbours' infested fields, *O. serotina* became established and formed dense monocultures on their lands.

> *"In 2005 they built this big drain ditch here but on the other side of the highway they did nothing. So on this side about three quarters of the field filled with water. It was like a lake. The flooding carries the seed all over. Before this flooding I had it just around the perimeter of the property and in a few bald spots on the field, but now it is all over the place"* – Les Becker

Another farmer posited that accelerated water flow was responsible not only for transporting seeds to neighbouring properties, but also carrying *O. serotina* to more distant locations.

> *"Water could take the seed longer distances too. The drainage ditch on my property is only 10 miles from Lake Winnipeg and is 150 feet above lake level. Water can wash into the lake quickly and the seed could easily be carried with it. It could end up on the shores of the lake or be carried north from there."* – Gary Kuz, farmer

Farm and municipal equipment also represent important dispersal vectors, but generally carry seeds over a limited range; all participants concurred that the primary means for *O. serotina* to traverse larger distances was the transportation of hay. The transport of forage crops has long been recognized as a vector for IAS (Davies and Sheley 2007) and the movement of hay across the landscape was cited as the cause of new populations of *O. serotina* that appeared several hundred kilometres from source populations.

Customarily harvested late in the summer when *O. serotina* has already set seed, the second cut of hay is regarded by most producers as the greatest source of *O. serotina* dispersion. Although they acknowledge that the risk is greater with the second cut of hay, Weed Supervisors advised that dispersion can also occur with the first cut of hay, even though it is harvested in June when *O. serotina* is still at the seedling stage.

> *"If those bales dropped onto a field with bartsia seed all over the surface, there will be bartsia on the outside of those bails."* - Fred Paulson

Normally most hay is traded locally. However, when environmental stressors such as flooding, disease, pests, hail damage or competition from other IAS affect other regions, the demand for hay from *O. serotina* infested areas increases. The most commonly cited catalyst for an increased demand for forage crops was drought, and under these conditions buyers sought sources from outside their immediate region. Because they were desperate to feed their livestock, they would also pay inflated process and be less selective. Many producers indicated that it was difficult to resist the temptation to sell potentially infested hay under these circumstances. It was during a period of drought in Western Manitoba in the 1980s, when demand for forage was high and hay was being shipped from all over the province that *O. serotina* first appeared in the region. Drought conditions have also been found to facilitate the establishment of invasive species (Jimenez *et al* 2011). Alberta has experienced drought conditions in recent years, suggesting that there is considerable risk of new *O. serotina* populations establishing there in the near future.

> "*Four years ago there was that big drought in Alberta, there were people baled-up for miles, with every kind of noxious weed, and it was shipped to Alberta. I can't imagine what they are going to have to deal with in the next few years!"* -John Johnston, Weed Supervisor

In 2011, widespread flooding occurred across Manitoba, inundating large tracts of agricultural land for much of the growing season and increasing the demand for forage, which in turn would have facilitated the spread of IAS.

3.4.3 Reponses to *O. serotina* Invasion

Table 3.1: Management approaches experimented with by participants

Management Approach	**Farmers** (n=20)	**Weed Supervisors** (n =5)	**Total** (n=25)	**Mean (SE) Impact of Control**[1]
Mechanical Removal (mowing or tillage)	18	0	19	1.37(0.17)
Manual Removal	17	0	17	2.47(0.06)
Herbicide Application	6	5	11	2.82 (0.12)
Compost Mulch Treatment	5	0	5	3.6(0.4)
Fertilizer Application	4	0	4	1.0(0.57)
Vector Management	4	0	4	1.0 (0.0)
Prescribed Burning	2	0	2	0.5 (0.0)
Mechanical Removal + Herbicide	2	0	2	4.0 (1.0)

[1] Impact of Control categories (based upon participants observations): 0= no control, infestation worsened; 1 = no change, infestations temporarily contained; 2= moderate (<30%) temporary reduction in infestation levels; 3= significant (>30%) temporary reduction in infestation levels; 4= significant long term reduction in infestation levels; 5) eradication

Participants had experimented with a wide range of management approaches attempting to mitigate the impacts of *O. serotina* with varying success (Table 3.1). Whereas hand-plucking some perennial invasive plants, like leafy spurge, actually facilitates their spread (Hanson and Rudd 1933), *O. serotina,* as an annual plant, is effectively controlled by this method. In so doing, some were able to eventually eradicate *O. serotina* from their property,

> "*A friend had it in his pasture, it was just red all around his house. Every year he had the whole family out plucking it and burning it. They had about five or six acres where they pulled it all out by hand, year after year. They collected garbage bags full and burned it. He keeps a close eye on it now. If he sees a plant he just pulls it out. I don't think he has any on his farm anymore.*" - Brian Yablonski, farmer

Many employed this control method and, although few were able to eradicate it completely, most managed to contain *O. serotina* populations over prolonged periods of time (Table 3.1).

Hobbes and Humphries (1995) suggest manual removal can only play a limited role in IAS control because of the labour intensiveness of this strategy. With *O. serotina,* it is critical to pull out all plants, before they set seed, and to repeat this process for many consecutive years, as it can remain dormant in the seedbank for over a decade (Roberts 1986). Given the struggles producers encounter managing their farming operations in addition to off-farm employment, this time consuming activity was not always feasible. Manual removal also required help from family or friends, which could be considered community building, a positive social outcome. Unfortunately, a steady and ongoing decline in the rural population made this labour-intensive management strategy increasingly unrealistic.

Others are more optimistic about our ability to overcome these labour deficit issues. Simberloff (2009) outlines several projects where convict labour was used to successfully eradicate IAS in the United States. School children have also been involved in many manual IAS removal projects in North America (e.g. Lagerquist 2007, Thompson 2010). As public awareness of the detrimental effects of IAS has increased, a volunteer labour force has begun to mobilize. Worldwide, eradication efforts such as many of those detailed in the Proceeding of the International Conference on Eradication of Island Invasives (Veitch and Clout 2002) have depended heavily upon the efforts of volunteer labour. Additionally, environmental non-government organizations (ENGOs) and social networking websites enable groups of concerned citizens to help with invasive species management, even in depopulated rural areas.

Not all management interventions require the eradication of established IAS populations. Another complementary approach of any containment strategy is to prevent further spread by controlling anthropogenic vectors (Ruiz and Carlton 2003, Davies and Sheley 2007). A number of human activities were responsible for *O. serotina* seed dispersal, which in turn gave rise to corresponding management responses. The most common of these responses was cleaning contaminated farm equipment before its movement to non-infested fields.

> *"We do custom baling, and before we go into the farmer's fields we wash our equipment in a car wash. We want to be good neighbours; so we figure we had better wash our equipment just to be on the safe side*." – David Yablonski, farmer

Many participants suggested that regulating the sale of hay could do much to limit the future spread of *O. serotina.* However, most concluded that this would be impossible to enforce. Weed Supervisor, John Johnston suggested that another model, currently employed in Alberta and many of the western states in the US, would be more appropriate. Referring to the North American Weed Management Association's Weed Free Forage Program, he explained, "*You actually have an inspector that comes out and inspects the fields and certifies that it is weed free. Producers can get a premium for the hay and the buyer knows he is getting a quality product*". As of 2010, the Manitoba Forage Council and the North American Weed Management Association were considering bringing this program to Manitoba (Petersen pers. comm.). However, it remains to be seen how effective this voluntary system could be; to date no studies have examined its efficacy in the jurisdictions where it has been adopted.

Another approach to *O. serotina* management applied by several farmers and Weed Supervisors was herbicide application. Some argued that herbicides were essential to weed management, and there have been numerous examples of IAS being successfully controlled through the use of chemicals (Sigg 1998). Weed Supervisors regularly applied herbicides such as Simazine 480 and 2,4-D dicamba to roadside *O. serotina* populations and most reported success at containing, albeit not eradicating, existing populations.

The MAFRI's (2011) fact sheet on *O. serotina* suggested that this IAS was effectively controlled by applying herbicides. However, farmers in the affected region found it difficult to use herbicides to control *O. serotina*. Most infestations occurred on marginal land unable to support annual crops, and applying herbicide to forage crops and pasture was complicated. Because most pastures and forage crops are polycultures, participants indicated that any herbicide selected to control *O. serotina* would also damage some desirable species. The broadleaf herbicides prescribed by MAFRI, which were effective at controlling *O. serotina*, were also injurious to legume species, such as alfalfa, which feature prominently in most forage crop mixtures. Some of the farmers who had experimented with this type of chemical controls abandoned the approach because of the ensuing damage. As a result, they noticed only temporary reductions in *O. serotina* abundance. As Fred Paulson pointed out, due to *O. serotina's* persistence in the seedbank, "*if you are not going to spray for a minimum of ten years, then you are wasting your time*." To accommodate a spray program, he suggested forage producers switch from the traditional, legume-grass mixtures to a single-species approach. However, a mixture of legumes and grasses produces a higher quality of forage than a monocrop system (Ball *et al* 2001). Other barriers to effective herbicide control were high costs, shortage of spraying equipment and inexperience in handling chemicals. According to participants the cost of chemicals amounted to $20 per acre, a significant expense for farmers who are already struggling to meet their bottom line. Those without the appropriate equipment needed to rent out sprayers or even hire operators to perform this service, which was even more costly.

Other responses to *O. serotina* invasions involved nutrient management. Most serious *O. serotina* infestations occurred on marginal agricultural land, whereas fertile lands suitable for annual crops remained unaffected, suggesting to many that there was a negative relationship between fertility and invasibility of land. However, during *O. serotina* herbicide control trials, Barry Todd, the Manitoba Department of Agriculture Weed Specialist, observed that in trial plots *O. serotina* abundance increased in response to fertilizer application (Interlake Forage Improvement Association 1982). Farmer Henry Jansen observed a similar result when applying conventional fertilizer to infested areas, "*I've never seen Red bartsia grow as tall as that before, because of the fertilizer*." Other farmers found that granular fertilizers did not affect the abundance of *O. serotina* in their fields. Nevertheless, most producers maintained that soil infertility increased susceptibility to invasion, like Brian Yablonksi, who indicated, "*fertility and Red bartsia infestation go hand in hand. Don't fertilize and Red bartsia shows up*." As a result, several attempted a wide diversity of approaches to increase soil fertility, to give desired species a competitive advantage against *O. serotina.*

One participant described how he reduced the abundance of *O serotina* on his property using a holistic approach to nutrient management. His grass-fed, direct-market beef operation consisted of hay with a stockpile re-graze, such that he would take one cut of hay off his fields annually, and use a rotational grazing system upon them in the fall and spring. According to Glen Nicoll, other forage producers removed too many nutrients from the system by taking two cuts of hay annually; hence they were not getting enough re-growth for competition. By taking only one cut of hay, and returning nutrients to the soil in the form of manure during rotational grazing, his approach allowed desirable species to remain healthy and competitive. Davies and Sheley (2007) further suggest that adjusting the timing of harvest can limit invasive species dispersal, which is another factor explaining the success of this system. Glen Nicoll explained that, "*when we cut our hay in late July or early August, Red bartsia is shorter. It has leaves on it but it isn't flowering yet*" Thus, he prevented seed dispersal with farm equipment. Despite the presence of *O. serotina* on his land over the last 20 years, it was never able to form thick monocultures that devastated farms elsewhere in the region.

Other farmers found that the application of thick layers of solid, composted manure (as mulch) over infested patches not only choked out *O. serotina*, but also stimulated the growth of desirable hay species. David Yablonski recounted that this control method was discovered accidentally, "*we hauled the manure down to the field in the fall, then we noticed the next year, where we hauled the manure the grass grew really good, and the Red bartsia wasn't there.*" He and a few of his neighbours found that this treatment suppresses the growth of *O. serotina* for several years following application. Dave Yablonski stressed the importance of properly composting the manure before applying it as mulch. His method took three years of preparation and required careful aeration.

Vasey (2008) found that areas treated with compost mulch had significantly lower mean *O. serotina* cover than those treated with 2,4-D or tillage, affirming the long-term efficacy of this treatment. Additionally, legume cover was significantly higher in fields treated with compost mulch than those receiving herbicide treatment or tillage, indicating that compost mulch has long-term benefits for desirable forage species. These benefits included improved water storage, increased organic matter and slow release of essential nutrients nitrogen, phosphorous and potassium into the soil (Pinamonti *et al* 1997, Deluca and Deluca 1997 Brown and Tworkoski 2004). However, it was unclear whether nutrient enrichment associated with mulching inhibited *O. serotina* growth. David Yablonski was skeptical whether nutrient-rich, liquid manure would be an adequate substitute for compost mulch treatment; instead he hypothesized that the important mechanism was mulch blocking sunlight and preventing *O. serotina* seed germination. Researchers examining the use of mulch to control another IAS found that mulch applied at a thickness of 3.7 cm provided about 90% control of the invasive, herbaceous, annual *Fatoua villosa* (Hairy crabweed) (Penny and Neal 2003).

Although, the use of compost mulch was successful, there were barriers to up-scaling this control method. Composted manure was scarce, and since it was applied in thick swaths, producers with widespread infestations were unable to treat entire fields using this method. Morover, specialized equipment was required to transport and spread compost mulch. Even those that used mulching as part of their weed management strategy considered the hauling of compost mulch as a limiting factor. They had been restricted to applying this treatment to fields nearest to where their supply of compost was situated. Many have large operations spread across the landscape, which they would be unable to treat with compost mulch. Finally, there was a potential for loading excessive nutrients into watercourses, this contributing to leaching and eutrophication of surface waters, especially in sandy soils (Eghball 2004). Nevertheless, the use of compost mulch remains a promising control technique and might become part of an integrated weed management strategy.

3.5 Implications of this Study

We found that farmers, property owners and Weed Supervisors, sharing knowledge accumulated through years of practical experience, can advance our understanding of the impacts, mechanisms and control of IAS. This is especially true of newly invading species such as *O. serotina* that are poorly understood. These lived experts have collected observations across many spatial and temporal scales. All participants in our study had many years of experience managing this IAS; indeed, some had been managing it for several decades under a wide variety of conditions. Drawing upon the knowledge base of these stakeholders provides insights into IAS that could not be achieved through traditional ecological science alone.

Our results highlight the importance of tracking the socio-economic and cultural implications of IAS. In human-dominated landscapes, IAS have anthropogenic causes and consequences. The LEK allowed us to gain a better understanding of the cumulative impacts of IAS on the environment and rural communities alike. IAS such as *O. serotina*, that have yet to cause significant ecological damage, can still have considerable socio-economic consequences. If IAS are only considered from a biological perspective, these other impacts could easily be overlooked. While the financial implications of *O. serotina* are clearly severe, our findings indicate that these impacts are much more than economic in nature. IAS can also contribute to strained relationships within communities and even within families, as well as contributing to a number of stress-related health risks faced by farmers, such as work place injury. Only by documenting the experiences of stakeholders can these impacts be adequately understood and mitigated.

Furthermore, many of these socio-economic impacts operate within an area affected by a broader social context. For example, little attention is given to the role of societal changes such as rural decline in the spread of IAS. Participants recognized that several demographic trends contributed to the spread of IAS including rural depopulation; increased sizes of farming operations; the leasing of land; and the need to work off-farm. These trends characterize rural communities across North America and other parts of the world (Alasia *et al* 2009, Pei *et al* 2009, Eastwood *et al* 2010, Duffy 2011). Thus, it is important to consider how these changes in rural human environments might contribute to the success of IAS wherever they occur.

Our research also demonstrates the value of farmer knowledge, an unexplored resource in the IAS literature, which otherwise continues to be dominated by biological sciences. In the broader socio-ecological literature as a whole, the value of Indigenous Knowledge and peasant knowledge in the context of the global south is widely recognized (e.g. Albertin and Nair 2004, Telfer and Garde 2006, Sears *et al* 2007, Degen *et al* 2010, Spoon 2011), but the importance of farmer knowledge in a northern context is largely overlooked. North American farmers in general, and even more so those who farm on marginal lands such as those affected by *O. serotina*, are often alienated from research and decision-making processes. As stewards of the land, they are forced to adapt to a variety of challenges, including IAS. Part of this adaptation process involves on-farm experimentation, which has long been regarded as a valuable source of knowledge (Rhoades *et al* 1995, Hoffmann *et al* 2007). Although its potential usefulness in the context of IAS management has been noted (e.g. Jordan *et al* 2003), very few studies have documented this type of farmer knowledge (Mauro and McLachlan 2008, Bart 2010). Our results clearly show the value of this lived expertise; the innovative IAS control strategies that emerged from this research could only have been discovered through years of on-farm, trial-and-error experimentation, and are much richer in nature and have more potential than the "spray-and-pray" approaches generally advocated by the government. In particular, the use of compost mulch shows promise as a means of controlling *O. serotina*, both in terms of efficacy and affordability. This inclusive research process, which is shaped by the participants and that reflects their lived expertise, arguably increases the likelihood that research outcomes will be relevant and meaningful to, and ultimately adopted by farmers and other stakeholders that have been affected by *O. serotina*.

The top-down approach prescribed by government agencies for the control of *O. serotina,* that is dependent on chemical control and cultivation, remains ineffectual. Direct dialogue with stakeholders, many of whom rely on word of mouth as their primary source of management information, is not only important for researchers because it can reveal innovative management approaches, but also for government agencies tasked with IAS control. Rather than continuing their strategy of promoting impractical or expensive management techniques, agriculture agencies such as MAFRI and Agriculture and Agri-Foods Canada should improve lines of communication with affected producers and work towards practical solutions in inclusive ways. This would not only increase the efficacy of control efforts, but might also alleviate producer suspicion of these government agencies.

The spread of IAS has implications for whole communities and regional environments. For management efforts to be successful across a large scale, collective action is required (Epanchin-Neill *et al* 2009). Given the complexity in organizing a diverse group of stakeholders, there is an opportunity for the government's agricultural representatives, Weed Supervisors and ENGOs to play an active role in coordinating a multi-sectoral and community-based management strategy. Especially in light of declines of within-farm support, this might involve organizing volunteers to help land managers overcome labour shortages, thus increasing the success of manual removal efforts. Another important component of IAS control that would benefit from improved lines of communication is EDRR. Agricultural representatives and Weed Supervisors could coordinate monitoring and mapping efforts, involving landowners in the process. IAS management provides many challenges, but could also provide opportunities to develop social capital and strengthen bonds within communities when given the appropriate level of government support.

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Chapter 4: A transdisciplinary approach to predicting the distribution of invasive *Odontites serotina* in Manitoba, Canada

4.1 Abstract

Species distribution models such as habitat suitability models are an important component of early detection and rapid response (EDRR) to invasive alien species (IAS). Red Bartsia (*Odontites serotina*) is a relatively new IAS for agro-landscapes in Manitoba but has been the focus of very few studies. Our overall goal was to gain insight into the combined role of local ecological knowledge and ecological data in better understanding the spatial dynamics of *Odontites serotina*. In particular, our objectives were to (i) describe the factors that underlie its spatial distribution; (ii) predict future occurrences of this IAS by matching a habitat suitability model with measures of propagule pressure to assess risk of invasion across the region; and iii) more generally explore the role of local knowledge in informing ecological modeling. We interviewed and conducted participatory mapping exercises with 20 farmers and 5 Weed Supervisors. By driving on roads, the occurrence of roadside and in field *O. serotina* was mapped at 0.2km intervals as was moisture, disturbance, ditch width, road class and surrounding land use. One set of these data was used to generate our predictive model (training data set) and one to test it (evaluation data set). The best model for predicting species occurrence includes land cover factors (forage, grassland and urban) soil characteristics (sandy texture, clay surface texture, and marginal agricultural capability); proximity to ditches or culverts; and the abundance of *O. serotina* in adjacent roadsides. This model had good predictive ability as assessed by the receiver operational characteristic (ROC), as the area under the curve (AUC) was .895 for the training data set and .891 for the evaluation data set. To formulate a more complete risk assessment for *O. serotina* we combined our predictive model with two measures of propagule pressure, distance to invasion foci and introduction effort. An overall risk map was created for the province of Manitoba, which will help direct future EDRR monitoring and outreach with farmers, weed inspectors, and the general public.

KEYWORDS: Agriculture; Invasive Alien Species, Propagule Pressure, Habitat Suitability, Predictive Model, Local Ecological Knowledge, *Odontites serotina;* socio-economic impacts

4.2 Introduction

Invasive alien species (IAS) are recognized as a serious threat to ecological integrity (Gordon 1998, Mack *et al* 2000, Charles and Dukes 2007), human health and wellbeing (Vitousek *et al* 1997, Binggeli 2001, Pejchar and Mooney 2009), and the economy (Pimental *et al* 2005, Kaiser 2006). Human presence and land use are inextricably linked to both the causes and consequences of IAS. The movement of IAS to new locations is often the result of anthropogenic activities, and human-altered landscapes, especially those related to agriculture, tend to be most susceptible to invasion (Mack *et al* 2000, McNeely 2001).

The importance of early detection and rapid response (EDRR) is increasingly emphasized in management strategies (Leung *et al* 2004, Westbrooks 2004), in large part because post-invasion management efforts of IAS are often expensive and unsuccessful (Rejmanek *et al* 2005). Many studies in recent years have focused upon developing predictive models known as ecological niche models, species distribution models or habitat suitability models (e.g. Thuiller *et al* 2005, Ficetola *et al* 2008, Sato *et al* 2010). These predictive models are crucial for prioritizing EDRR monitoring and management efforts because they identify areas at risk of future invasion (Byers 2002). These models usually relate species occurrence data to environmental variables in order to map potential invasive species distributions; however, most of these studies have been at large scales and emphasized coarse variables such as climate (e.g. Peterson 2003, Thuiller *et al* 2005, Chen 2007). Although these models are useful, climate conditions alone may not always accurately predict limitations in plant distributions (Davis *et al* 1998, Peterson 2003, Welk 2004). Fewer studies have considered the influence of more localized environmental variables such as soil characteristics and hydrology (Rouget *et al* 2001, Rouget and Richardson 2003). These models thus fail to account for some important mechanisms of species invasions, including the invading species biology, and interactions between biotic and abiotic factors (Richardson *et al* 2004, Thuiller *et al* 2005). Even fewer have accounted for variables related to anthropogenic land use, which strongly influence susceptibility of ecosystems to invasion (McNeely 2001). To our knowledge, none of these habitat suitability models has yet incorporated the local knowledge of farmers or weed management professionals.

Local ecological knowledge (LEK) is based upon people's placed-based observations of their environments and accumulated over a lifetime (Anadon *et al* 2009). In this, LEK represents a cumulative body of knowledge handed down through generations (Berkes *et al* 2000). Particularly valuable in cases where people's livelihoods are directly linked to ecosystem services, often LEK involves indigenous people, (Berkes *et al* 2003) but also farmers (Chalmers and Fabricius 2007, Mauro and McLachlan 2008). It is recognized as a valuable means of enhancing conventional ecological studies that seek to understand complex issues spanning multiple spatial and temporal scales (Brook and McLachlan 2009, Peloquin and Berkes 2009), LEK is an important source of region-specific information about the local ecology of species and the socio-economic implications of environmental issues (Hood *et al* 2009). However, very few ecological studies of any sort incorporate LEK, although this number is increasing (Brook and McLachlan 2008).

Although it is valuable to identify suitable areas for IAS establishment through habitat suitability models, these species are less likely to be limited by habitat requirements than by propagule availability (Rouget and Richardson 2003, Holle and Simberloff 2005). Therefore, habitat suitability models alone are not sufficient to assess the risk of invasion. The importance of propagule pressure, the probability that an invasive species will be introduced to a given area, as a mechanism of species invasions, has been widely acknowledged by ecologists (Williamson 1996, Lonsdale 1999, Lockwood *et al* 2005, Simberloff 2009). However, few studies modeling the potential distribution of IAS have accounted for its role in the invasion process (Guisan and Zimmerman 2000, Lockwood *et al* 2005). Rouget and Richardson (2003) incorporated propagule pressure into an invasive plant distribution model by measuring distance to invasion foci, or source populations. Herborg *et al* (2007) used introduction effort, specifically the amount of ballast water released at various ports in the USA, as a measure of propagule pressure which they matched with habitat suitability to estimate the risk of *Eriocheir sinensis* (Chinese mitten crab) establishment. To forecast the potential distribution of *Didemnum vexillum* (colonial tunicate) along the coast of British Columbia, Herborg *et al* (2009) combined an ecological niche model with five transport vectors associated with its spread.

Our overall goal was to better understand the combined role of local ecological knowledge and ecological data in better understanding the spatial dynamics of *Odontites serotina*. In particular, our objectives were to (i) describe the factors that underlie its spatial distribution; (ii) predict future occurrences of this IAS by matching a habitat suitability model with measures of propagule pressure to assess the risk of *O. serotina* invasion across the region; and iii) more generally explore the role of local knowledge in informing socio-ecological modeling.

4.3 Materials and Methods

O. serotina in Manitoba

Odontites serotina (Red bartsia) is an IAS that is currently devastating pastures and haylands in Manitoba's Interlake region. Although it has the potential to cause widespread damages across the Canadian Prairies (Chapter 3), it has been the focus of few studies. Adapted to a wide range of climate conditions, *O. serotina's* distribution in its native range extends throughout most of Europe from Scandinavia to Portugal, Greece and Turkey (Marhold 2011). As a hemiparasite, *O. serotina* forms opportunistic, parasitic relationships by establishing haustorial connections on the roots of host plants. Even a small population of hemiparasites can have significant impacts upon community structure and function (Press and Phoenix 2005). Associations with host plants, such as *Medicago* *sativa* (alfalfa), enable hemiparasites of the *Odontites* genus to grow larger with an increased resistance to herbivores, while also reducing host plants' productivity and defenses against herbivores (Matthies 1995, Adler 2000, Puustinen & Mutikainen 2001). Known to benefit from associations with a wide range of host species (Govier *et al* 1967), *O. serotina* thrives even during periods of drought (Snogerup 1982). As a prolific seed producer, each individual is capable of producing up to 1400 seeds (MAFRI 2011), which further facilitates its ability to colonize established vegetation, and to form dense monocultures.

Like many IAS, the success of *O. serotina* is closely linked to human activity. Anthropogenic activities such as transportation of forage crops, municipal road maintenance and the movement of farm machinery are common dispersal vectors, while human disturbances such as mowing and harvesting of forage crops facilitate *O. serotina's* establishment (Chapter 3). As it is unpalatable to livestock, infestations can have significant economic consequences to agricultural producers (Chapter 3). Although *O. serotina* is technically controlled by cultivation and herbicide application (MAFRI 2011), these techniques are not feasible for most livestock and forage crop producers (Chapter 3). It thus has tremendous impacts on individual producers and rural communities, but these impacts much less the mechanisms underlying its success in its invasive range remain poorly understood.

Study Area

We conducted this study in the Interlake Region, which is situated in south-central Manitoba between Lake Manitoba and Lake Winnipeg. This area is located within the Interlake Prairie ecoregion: a transition zone marking the southern limit of closed Boreal Forest and the northern extent of open arable agricultural land (Smith *et al* 1998). Native vegetative cover in the area is predominantly aspen hardwood and aspen mixedwood forest, and low-lying areas are covered with sedges and willows (Smith *et al* 1998). The region also contains some rare vegetation community types including tallgrass prairie and alvar-like vegetation communities (Hamel and Foster 2004, Manitoba Conservation Data Centre 2011). About 40% of the region is farmland, of which 25% is forage crop or pasture and 15% is annual crop (Manitoba Conservation 2002). The main crops are alfalfa (*Medicago satvia*) and alfalfa mixtures, tame hay/other fodder, canola (*Brassica napus)* and oats (*Avena sativa*) (Statistics Canada 2006). Livestock production focuses largely on cattle and hogs (Statistics Canada 2006). Soils of the region are Dark Gray Chernozems overlying dolomites and limestone of the Red River Formation. Extensive calcareous, loamy, stony till deposits in the region are interspersed with stone-free clay till with little slope (0-2%). Due to poor drainage and soil characteristics, cultivated crops are generally difficult to establish in this region (Podolsky 1986). The climate is continental, with a mean annual temperature of 1.8ºC; the mean minimum in January is -18.7 ºC and mean maximum July is 18.9 ºC (Environment Canada 2011). The average annual precipitation is 526.4 mm per year, of which 409 mm falls as rain (Environment Canada 2011).

We divided our study region in two. The first represented the region in which *O. serotina* was initially established in the province. This invasive plant was first identified in Manitoba at the Gimli airport in 1954 (Scoggan 1957) and was first reported in the rural municipality (RM) of Armstrong in the 1960s (Paulson, pers. comm.). We used this as our main study area, where we documented species occurrence as well as environmental variables (i.e. model development area). After a lag period, *O. serotina* has begun to spread rapidly to neighbouring regions in recent years. We sampled two recently invaded areas in the RM of Bifrost and the RM of Siglunes to evaluate the effectiveness of our model (model evaluation area). The same species occurrence data and environmental variables were collected for both the model development and model evaluation areas.

Data collection

Local Ecological Knowledge

The LEK of farmers and Weed Supervisors with experience managing IAS, and *O. serotina* in particular, was documented as part of this study. Prior to beginning interviews, all questions and methodologies were subject to an ethics review by the Joint Faculty Human Subject Research Ethics Board Protocol at the University of Manitoba. This review ensured that the project met all ethical guidelines. It was granted approval under project number (#J2007:018). In total, 20 farmers and five Weed Supervisors were interviewed. All of the farmers had a long history of managing this species. Weed Supervisors, employed locally by Rural Municipalities (RMs) to control noxious weeds on public property and enforce the province of Manitoba's Noxious Weed Act (Manitoba Weed Supervisors Association 2011), all have extensive training in IAS and weed management. Those who participated in this study have been managing *O. serotina* in their Weed Districts for at least 15 years.

We documented LEK through semi-structured interviews (Bernard 2000), which included a participatory mapping exercise (Kailbo and Medley 2007). Participants mapped the history of *O. serotina* invasion on their land, or within their weed district, delineating its movement spatially and over time. They also identified and mapped out ecological and land management factors that they observed to be associated with *O. serotina's* establishment and spread. Maps were hand drawn on orthophotos and later digitized into GIS (ArcMap 9.3, ESRI, USA).

Ecological Data

Employing a prospective sampling technique (Fielding and Bell 1997), we collected two independent presence/absence data sets for *O. serotina*: the training data set used to calibrate the model and the evaluation data set to test the predictive ability of the model (Guissan and Zimmerman 2000). The training data set was collected for the RM of Gimli and Armstrong where, according to historical Weed Supervisor records, *O. serotina* first became established in the early 1960s. In turn, the evaluation data set was collected within the RM of Siglunes and Bifrost where *O. serotina* was first identified in the 1990s. Roadside and field habitats along rural grid roads and highways were surveyed in four townships for each of the data sets. All roads within each township (6 x 6 mi) were sampled by two researchers within a vehicle travelling at a constant speed of 30 km/h. Presence/absence and percent cover data for *O. serotina* were collected for all field and roadside habitats at 200m intervals. Surrounding land use/land cover for each interval point was classified into seven categories: forage, grassland (including native grassland and pasture), trees (including deciduous, coniferous and mixedwood forests), annual crop, wetland, water and urban/transport following Agriculture and Agri-Food Canada (2004, p.55), while disturbance events and any hydrological features were also recorded. Data were later transcribed to polygons using GIS (ArcGIS 9.3, ESRI inc. USA) by referencing aerial photographs (Manitoba Government and LINNET Geomatics International 1998) to determine land cover boundaries. Union overlay analysis was then preformed with these land cover polygons to obtain corresponding soil characteristics (Western Land Resource Group 2002). To extrapolate the predictive model over a larger scale, province wide land use/land cover (Manitoba Conservation 2002) and hydrological features data (Manitoba Conservation 2004) were derived from GIS layers obtained through the Manitoba Land Initiative, Manitoba Conservation (Manitoba Land Initiative 2011).

Data Analyses

Local Ecological Knowledge

Interview transcriptions were imported into Atlas.ti (Muhr 1997), where they were reviewed, coded thematically (Berg 2001) and later consolidated into the broader themes that inform these results. We used a mixed methods approach whereby interview themes were matched to the outcomes of the quantitative data analysis to complement, support, and shape the quantitative analyses (Creswell 2009). Explanatory variables that arose from the interviews and participatory mapping exercises, particularly those that were most frequently referenced, or closely related to IAS literature, were used to develop candidate models for predicting *O. serotina* occurrence.

Modelling Approach

For the training data set, we used binary logistic regression (SAS, Version 8.3), to determine the factors influencing *O. serotina* occurrence and to identify habitats most suitable for *O. serotina* establishment. A set of candidate models was developed that we hypothesized to influence *O. serotina* occurrence using 12 predictor variables. These independent variables emerged from the knowledge of farmers and Weed Supervisors who participated in this study as well as the literature. Variables were first screened for excessive collinearity using a Spearman rank correlation matrix for all possible pairs of independent variables. If any two variables had $r>0.7$, the less important variable was removed.

One potentially serious shortcoming of species distribution modeling is spatial autocorrelation (Dormann *et al* 2007, Fielding and Bell 1997, Guisan and Thuiller 2005, Araujo *et al* 2005). Because species occurrences tend to be spatially clustered, and environmental conditions tend to be more similar at closer locations, the explanatory power of environmental variables can be erroneously inflated in spatial models. One common method of mitigating any effects of spatial autocorrelation is to incorporate a term for spatial autocorrelation, an autocovariate, into the analysis (Lichstein *et al* 2002). However, models that incorporate such a measure will not be applicable in other locations because the arrangement of environmental variables is not uniform across different regions (Guissan and Thuiller 2005). Hence, models including an autocovariate cannot be extrapolated to regions where no species occurrence data are available (Segurado *et al* 2006).

Given our goal of extrapolating our model across the province of Manitoba, the inclusion of an autocovariate in our model was thus infeasible. Instead, once the sets of candidate models were developed, model fit was assessed using an information-theoretic approach (Burnham and Anderson 2002), which is less sensitive to spatial autocorrelation because it is not reliant on significance thresholds (Westphal *et al* 2003, Segurado *et al* 2006). Akaike's information criterion difference (ΔAIC_c) and Akaike weights (*w*) were used to assess the fit of all models and to identify the model with the lowest ΔAIC. Akaike weights provide a normalized comparative score for all models and are interpreted as the probability that each model is the best model of the set of proposed models (Anderson *et al* 2000). Substantial support for a model occurs when $\Delta AIC < 2$. Cumulative AICc weights were calculated for each independent variable thought to influence *O. serotina* presence by summing the AICc model weights of every model containing that variable (Burnham and Anderson 2002). Variables with the highest cumulative AICc weights have the greatest influence on *O. serotina* occurrence. The model was then used to derive relative probabilities of *O. serotina* presence for all habitat polygons in the study area, using probit analysis (Stata software version 11.0). As relative probability values approach 1, the polygon is interpreted as having a relatively high suitability for *O. serotina* establishment

The AIC analysis is useful for model selection and averaging, but does not provide insights into the predictive capacity of the model (Pearce and Ferrier 2000). To evaluate the performance of the obtained model, predicted habitat suitability scores were compared against observed presences and absences. Three main accuracy measures were calculated (SPSS, version 16.0) from the resulting confusion matrix (Fielding and Bell 1997): (i) specificity (the proportion of true negatives or absences); (ii) sensitivity (the proportion of true positives or presences); and, (iii) the total area under the receiver operational characteristic (ROC) curve (AUC). The ROC curve plots sensitivity values on the y-axis against 1- specificity values on the x-axis. AUC values range from 0-1, if values are below 0.5 the model does not predict occurrence better than the random points, values over 0.7 indicate that the model is acceptable, and 1.0 represents a prefect model (Swets 1988). AUC was chosen as an accuracy measure because it is less sensitive to spatial autocorrelation than other statistical methods such as likelihood ratio test statistics (Segurado *et al* 2006). Model performance was then tested with the evaluation data set from the more recently invaded areas in the RMs of Bifrost and Siglunes. The model was then extrapolated across all RMs located within the agricultural regions of southern Manitoba.

Measures of Propagule Pressure

In addition to the habitat suitability model, to more accurately assess the relative risk of invasion for each RM, we calculated two measures of propagule pressure. Following Rouget and Richardson (2003) we included a measure of distance-to-invasion foci. For each RM, we calculated the average distance to *O. serotina* source populations. To identify source populations, we included species occurrence data collected during this study as well as all available records from Weed Supervisors from across the province. In GIS (ArcMap 9.3, ESRI, USA), Euclidean distance to these source populations was measured for each 1 hectare-cell across the province. Zonal statistics were then calculated to determine the mean distance to the nearest source population for each RM (Figure 4.5). However, this measure alone does not account for dispersal vectors, which are another important contributor to propagule pressure. Following Herborg *et al* (2007), we included a measure of introduction effort and calculated the total non-commercial feed purchased in each RM (Figure 4.6), which is hay or feed that is not traded through a regulated source but rather from farmer to farmer (Statistics Canada 2006). With these two measures of propagule pressure (P) we calculated the relative risk of introduction for each RM, which we combined with the habitat suitability or probability of survival (S) to define the relative risk of invasion (P*S).

4.4 Results

Local Ecological Knowledge

All of the Weed Supervisors and farmers who participated in this study had at least 15 years of experience dealing with *O. serotina* as an IAS in their communities and on the land they managed. Most farmers had been adversely affected, and in many cases the economic costs associated with this IAS were considerable, in terms of lost productivity of land, and time and resources spent on control efforts. "*This is hurting; it is by far the biggest challenge I've had to face as a cattle producer*" –Larry Nosaty, farmer. Many small-scale farmers interviewed expressed similar sentiments. On average, participating farmers spent 112 hours and $2,152 per year controlling *O. serotina*. Despite these efforts, they lost on average $8,215 per year in productivity, a substantial amount for farms in a region dominated by marginal farmland. However, *O. serotina* was only a minor inconvenience for the sole large-scale forage producer interviewed, in part because he used a mono-crop system and frequently rotated in annual crops, and thus was able to use herbicides extensively.

Participants identified a diversity of human-altered landscapes as the most susceptible to invasion (Table 4.1). Hay and pasture fields, as well as residential lawns, urban areas and transportation corridors were the most commonly infested areas, although some had also observed this IAS in natural grasslands and open meadows.

Table 4.1: Landscapes participants associated with *O. serotina* infestation

TYPE OF LANDSCAPE	FARMERS (N=20)	WEED SUPERVISORS (N =5)	TOTAL (N=25)
Perennial Forage or Haylands	20	5	25
Pasture	20	5	25
Roadsides or Transportation Corridors	20	5	25
Residential or Urban Areas	20	3	23
Native Grasslands or Open Meadows	4	1	5
Forests	2	0	2
Wetlands	0	0	0
Annual Crops	0	0	0

In contrast, annual crops were not commonly infested,

> "*I've never seen it (O. serotina) on annual crop land. It establishes itself on roadsides and lower productivity land that is hard to renovate, so native forages, native pastures and stony land that hasn't been broken with native bush on it"* -George Willis, Weed Supervisor

Moreover, *O. serotina* was frequently associated with nutrient deficient soils, particularly sandy or rocky soils.

> "*I think that the fertility of the soil and Red bartsia infestation go hand in hand. It is usually takes over stony fields, with poorer quality soil, where it has less competition."* -Brian Yablonski, farmer

Farmer observations supported research indicating that *O. serotina* is a generalist hemi-parasite, capable of exploiting a wide range of host species (Govier *et al* 1967). However, some farmers noticed that graminoid species, such as Timothy (*Phleum pratense*), had a better survival rate in infested areas than legumes such as alfalfa (*Medicago sativa*) and clovers (*Trifolium spp.*).

> *"It seems like where the Red bartsia grows it kills off all the plants around it. Nothing grows as well around it, especially your alfalfa. You'll still get some Timothy, but the alfalfa won't grow"* – Joeseph Cherniak, farmer

Although the degree to which their operations had been adversely affected by *O. serotina* varied, all participants were concerned that *O. serotina* would continue to spread. "*It is guaranteed that it is moving across the province and it is going to be a threat in some areas*" Fred Paulson, Weed Supervisor.

Marginal farmlands were seen as particularly vulnerable,

> *"Some areas are at risk. Pretty much any part of the province that has Class 4 or 5 soils. Areas with pasture and hay areas with bush that are overgrazed."* -Glenn Nicoll, farmer

Participants perceived that proximity to existing populations was highly correlated with risk of establishment. Adjacent roadsides and neighbouring fields that had been infected were often seen as the source of propagules for new introductions.

> *"Unless everybody is going to control it on their land it is a losing battle. Your neighbour could be retired and he doesn't care, or other people just buy the land to put up a house, don't farm it and they don't care. And it spreads from the roadside, that's how it gets going. My neighbour has been trying to control it on his land, his field is fine now, but it is sitting along the road, so it is going to come back anyway. The wind will blow it in, or with the snow melt, it will end up along the edge of the field."* - Bernice Shurek, farmer

Although natural dispersal vectors, such as water, were recognized as playing a role in dispersing *O. serotina*, the most common vectors were anthropogenic (Table 4.2),

> *"Guys grow hay on land infested with Red bartsia and transport it around, so even though they are doing a good job of spraying up there, they always have a new source of seed falling out of trucks. And it is not just through hay. People will drive down a dirt road and their tires will pick up seed and drop it off somewhere down the line. Although this is not huge movement, it can eventually cause infestations to develop."* -Glen Hnatiuk, Weed Supervisor

Human alterations to the hydrological cycle, such as drainage ditches and culverts, were believed to be responsible for accelerating the spread of seeds across the landscape. Many identified flooding resulting from newly constructed ditches or culverts as important points of introduction,

> *"At that time John's field (*adjacent*) was just covered with Red bartsia, so it wasn't that far for the seed to travel. The biggest thing was the drainage ditch. It couldn't have spread from within this field because I was plucking it out before it could go to seed. But it kept coming in from the drainage ditch, and eventually it took off from there".* – Larry Nosaty, farmer.

Farm equipment, all terrain vehicles (ATVs), municipal mowers and graders, were also seen as responsible for facilitating the spread of this IAS within the RM. However, all identified transport of forage crops, particularly the transfer of hay among producers, as the primary long-range dispersal vector for *O. serotina* (Table 4.2).

Table 4.2 : Dispersal Vectors identified by Interview Participants

DISPERSAL VECTOR	FARMERS (N=20)	WEED SUPERVISORS (N =5)	TOTAL (N=25)
Transportation of Forage Crops/ Hay	20	5	25
Farm Equipment	16	3	19
Municipal Road Maintenance Equipment	15	3	18
Off-Road Vehicles	10	4	14
Water	11	0	11
Animals	8	2	10
Alterations to Hydrology	5	0	5
Wind	3	0	3

Factors contributing to *O. serotina* invasion in Manitoba's Interlake Region

Roadside monitoring showed that invasive *O. serotina* occurred within 823 (24%) of the 3360 habitat polygons and also occurred along 1329 (40%) of 3360 of the adjacent roadsides within the main study area. It was most abundant in forage crops, but it was also commonly observed in grasslands and in urban/transport land use (Table 4.3).

Table 4.3: Habitat Polygon and roadside mean *O. serotina* percent cover for each of the land use/land cover categories within the main study area

Land Use/ Land Cover		Roadsides		Habitat Polygons	
	n	Mean	SE	Mean	SE
Forage	718	3.31^{a}	0.34	11.32^{a}	0.69
Urban/Transport	301	2.97^{a}	0.63	3.06^{b}	0.48
Grassland	1011	2.57^{b}	0.25	2.04^{b}	0.26
Trees	1175	1.95^{c}	0.56	0.07^{c}	0.02
Annual Crop	343	0.49^{c}	0.16	0.03^{c}	0.03
Wetland	112	2.49^{c}	0.14	0.01^{c}	0.01

Means followed by the same letter lack statistical significance according to post hoc multiple means Tukey test ($p < 0.05$)

Using the Local Knowledge of farmers and Weed Supervisors (Table 4.4) we identified twelve independent variables (Table 4.5), that were used to generate nine plausible models to represent factors affecting the presence of *O. serotina* (table 4.6). Factors that were most frequently identified as important by participants were all included. Others factors that were supported by the biological literature were also used, even though they were less frequently referenced in interviews. These included: anthropogenic land cover classes, soil characteristics, whether or not there is a municipal herbicide control program, and measure of proximity to hydrological alterations and source populations.

Table 4.4: Factors identified by participants as being associated with *O. serotina* presence/absence in habitat polygons included in AIC analysis.

FACTOR	FARMERS (N=20)	WEED SUPERVISORS (N =5)	TOTAL (N=25)	INDEPENDENT VARIABLE ABBREVIATION
Land cover: perennial forage or haylands	20	5	25	Forage
Land cover: pasture or native grassland	20	5	25	Grassland
Land cover: Residential or Urban areas	20	3	23	Urban
Marginal/Low productivity soils	14	5	19	Marginal
Sandy soils	8	2	10	Sandy
Gravel roads (bumpy, seeds fall off trucks in transit)	8	3	11	GravelRoad
Water retaining soils	6	1	7	Claysurface
Presence/absence of municipal roadside spray program	6	1	7	Spray
Abundance of OS in adjacent roadsides	6	0	6	Ditch_%
Proximity to roadside populations	6	0	6	Dist_Roadside
Proximity to anthropogenic alterations to hydrology	4	1	5	Dist_Ditch
Low lying areas	5	0	5	LSMean

Table 4.5: Explanatory variables used to develop the set of models to predict the presence of *O. serotina* in fields in Manitoba's Interlake region

ABBREVIATION	VARIABLE	SOURCE[1]
Forage	In field land is used for forage crop production (yes, no)	LK
Grassland	In field land is used for pasture or native grassland (yes, no)	LK
Urban	In field land is urban/residential use (yes, no)	LK
Dist_to_Road	Distance of polygon to nearest road (m)	Both
Dist_Ditch	Distance of polygon to nearest culvert or drainage ditch (m)	Both
Ditch%	Abundance of O. serotina on adjacent roadsides (percent cover)	Both
Gravelroad	Field is adjacent to a gravel road (yes, no)	LK
LSMean	Slope and steepness factor of soil calculated with the Universal Soil Loss Equation (Western Land Resource Group 2002)	Both
Sandy	Soils classified as sandy in texture (Western Land Resource Group 2002) (yes, no)	LK
Marginal	Agricultural Capability of Soil is Class 3-5 (Western Land Resource Group 2002) (yes, no)	LK
Spray	Weed Supervisor treats adjacent roadsides with herbicide to control O. serotina (yes, no)	LK
Claysurface	Surface texture of soils is clayey (Western Land Resource Group 2002) (yes, no)	Both

[1] Local Knowledge (LK) or Both LK and literature

Spearman rank correlation among the 12 variables ranged from .0037 to .6294, thus all of the variables were included in the model. Six of the models had a ΔAIC < 2 (Table 4.6); the best fit was Forage + Grassland + Urban + Sandy + Claysurf + Marginal + Ditch% + Dist_Ditch with ΔAIC = 0.

Table 4.6: Number of model parameters, differences in Akaike information criterion, and AICc weights (w) for candidate spatial models developed for in field *O. serotina* populations in Manitoba's Interlake Region

MODEL STRUCTURE	-2LOG(L)	K	ΔAIC.	AKAIKE WEIGHT
Forage+Grassland+Urban+Sandy+Claysurf+Marginal+Ditch%+DistDitch	2179.16	9	0	0.107
Forage+Grassland+Urban+Sandy+Claysurf+Marginal+Ditch%+GravelRoad+DitchDist	2177.95	10	0.805	0.072
Forage+Grassland+Urban+Sandy+Claysurfl+Ditch%+DitchDist	2182.61	8	1.442	0.052
Forage+Grassland+Urban+Sandy+Claysurf+Marginal+Ditch%+DitchDist+spray	2178.87	10	1.718	0.045
Forage+Grassland+Urban+Sandy+Claysurf+Marginal+Ditch%+DitchDist+LSMean	2178.92	10	1.767	0.044
Forage+Grassland+Urban+GravelRd+Claysurf+Sandy+Ditch%+DitchDist	2178.96	10	1.810	0.043
Forage+Grassland+Urban+Sandy+Claysurf+Ditch%+DitchDist+Spray+DisttoRoad	2182.27	10	5.125	0.008
Forage+Grassland+Urban+Claysurf+DisttoRoad+Marginal	2213.22	7	30.039	<0.001
Forage+Grassland+Ditch%+Sandy+DisttoRoad+Marginal+DitchDist+Spray+Claysurf	2587.72	10	410.566	<0.001

Summation of the Akaike weights (Burnham and Anderson 2002) for the independent variables (Table 4.7) resulted in the highest possible value (1.00) for four variables: forage cover, grassland cover, and urban cover, as well as distance to the nearest human-modified hydrological flow (e.g. drainage ditch or culvert). These results highlight the relative importance of anthropogenic factors in the successful establishment of this IAS. Land cover classes that were highly correlated with *O. serotina* presence were human-altered. Proximity to drainage ditches or culverts was an important variable in our model, indicating the importance of water as a dispersal vector and how human-altered drainage has facilitated the movement of *O. serotina* across the agri-landscape. Abiotic soil characteristics including sandy texture (0.95) and clay surface texture (0.92) were also highly important explanatory variables. Abundance of *O. serotina* in adjacent roadside habitats (0. 88) was also important, suggesting that roadsides populations were sources of propagule pressure for in field infestations.

Table 4.7: Cumulative AICc weights (w) for all twelve independent variables hypothesized to influence the presence of *O. serotina*.

VARIABLE[1]	CUMULATIVE AIC_C WEIGHT[2]
Forage	1.00
Grassland	1.00
Urban	1.00
Dist_ditch	1.00
Sandy	0.95
Claysurf	0.92
Roadside%	0.88
Marginal	0.64
Gravelroad	0.41
LSMEAN	0.34
Spray	0.30
Dist_toRoad	0.29

[1] Variables are described in table 4.6

[2] Cumulative AICc weight of a variable=the percent of weight attributable to models containing that particular variable and is calculated by summing the AICc model weights of every model containing that variable

The AUC of the model was 0.895 (sensitivity 0.628, specificity 0.900) indicating a satisfactory performance of the model (Figure 4.2). For the second evaluation data set, the AUC was only slightly lower at 0.891 (sensitivity 0.696, specificity .983) strongly supporting the predictive capacity of the model (Figure 4.4).

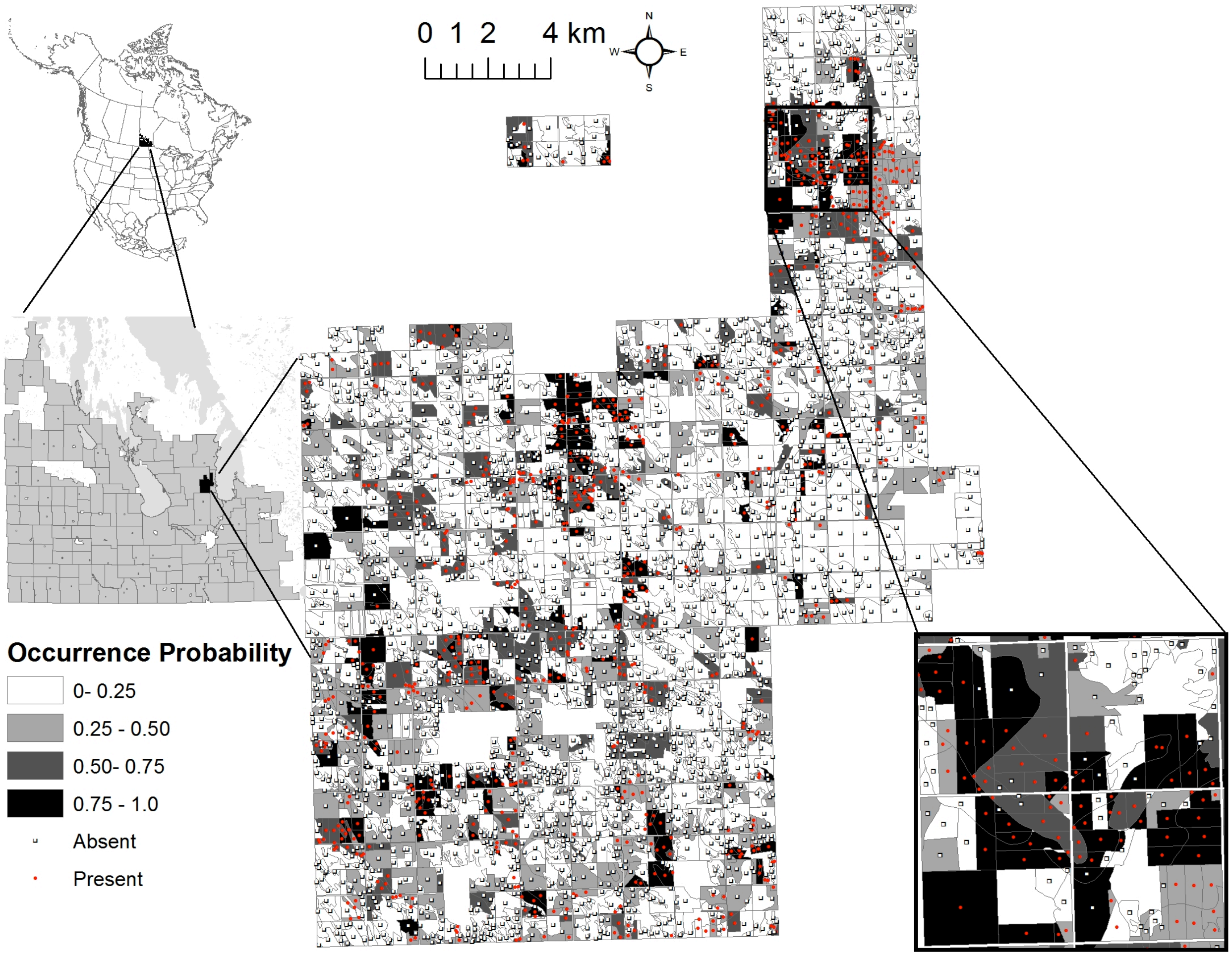

Figure 4.1: Predicted potential distribution of *O. serotina* in the primary study area in the RMs of Armstrong and Gimli (training data set) with presence and absence data.

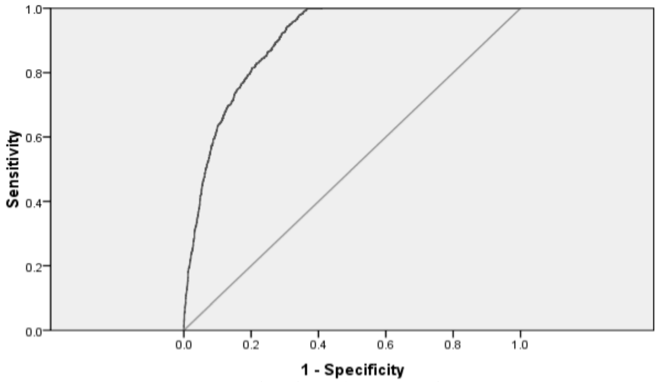

Figure 4.2: ROC curve for the primary study area (AUC= .895)

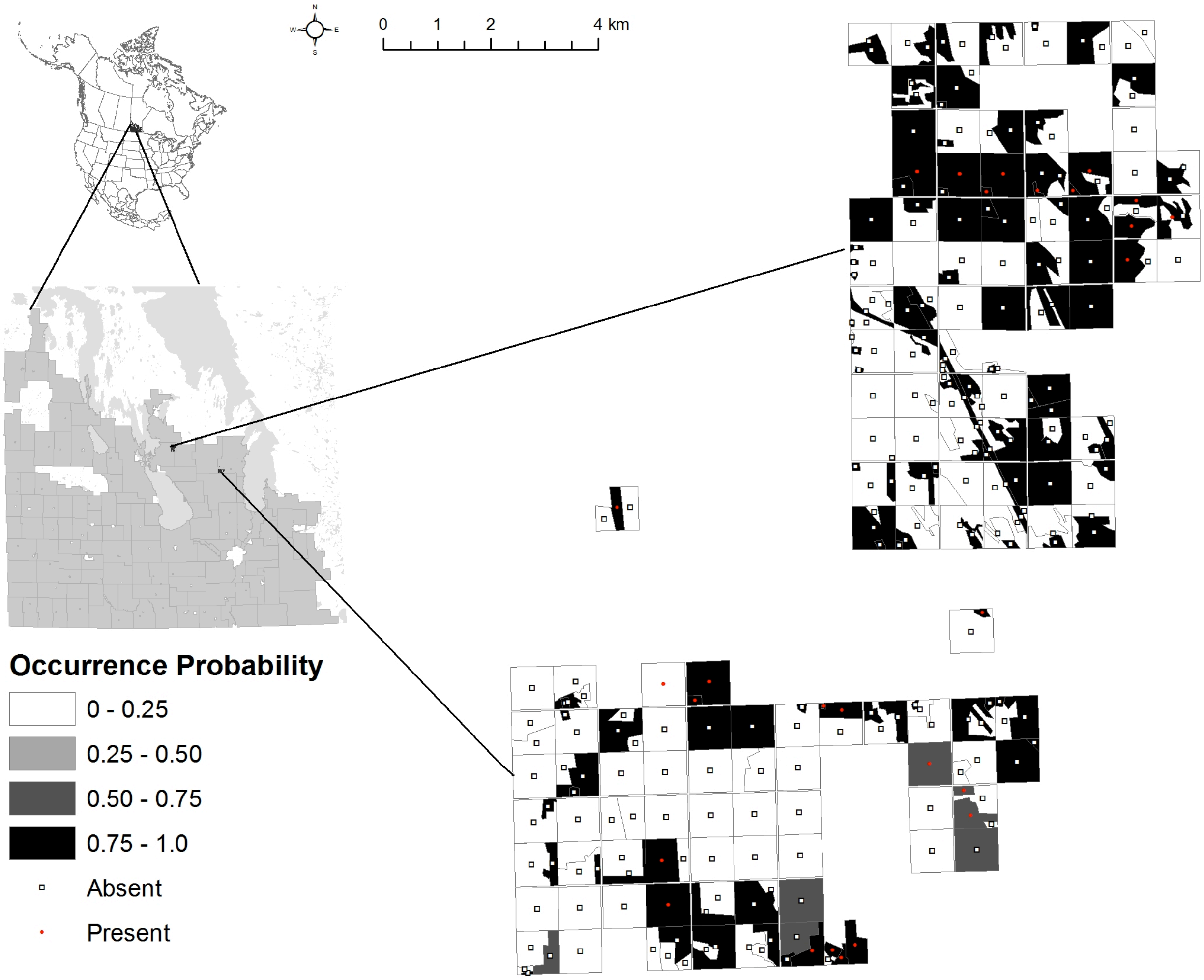

Figure 4.3: Predicted potential distribution of *O.serotina* in recently invaded areas in the RMs of Siglunes and Bifrost (evaluation data set) with presence and absence data.

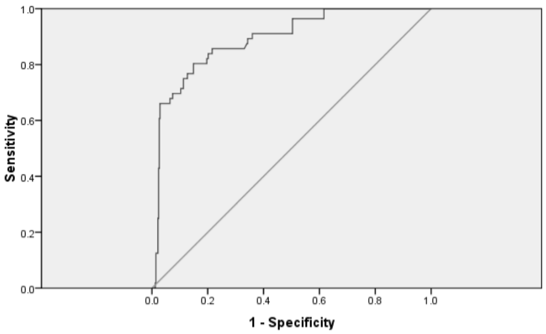

Figure 4.4: ROC curve for evaluation data set (AUC: .891)

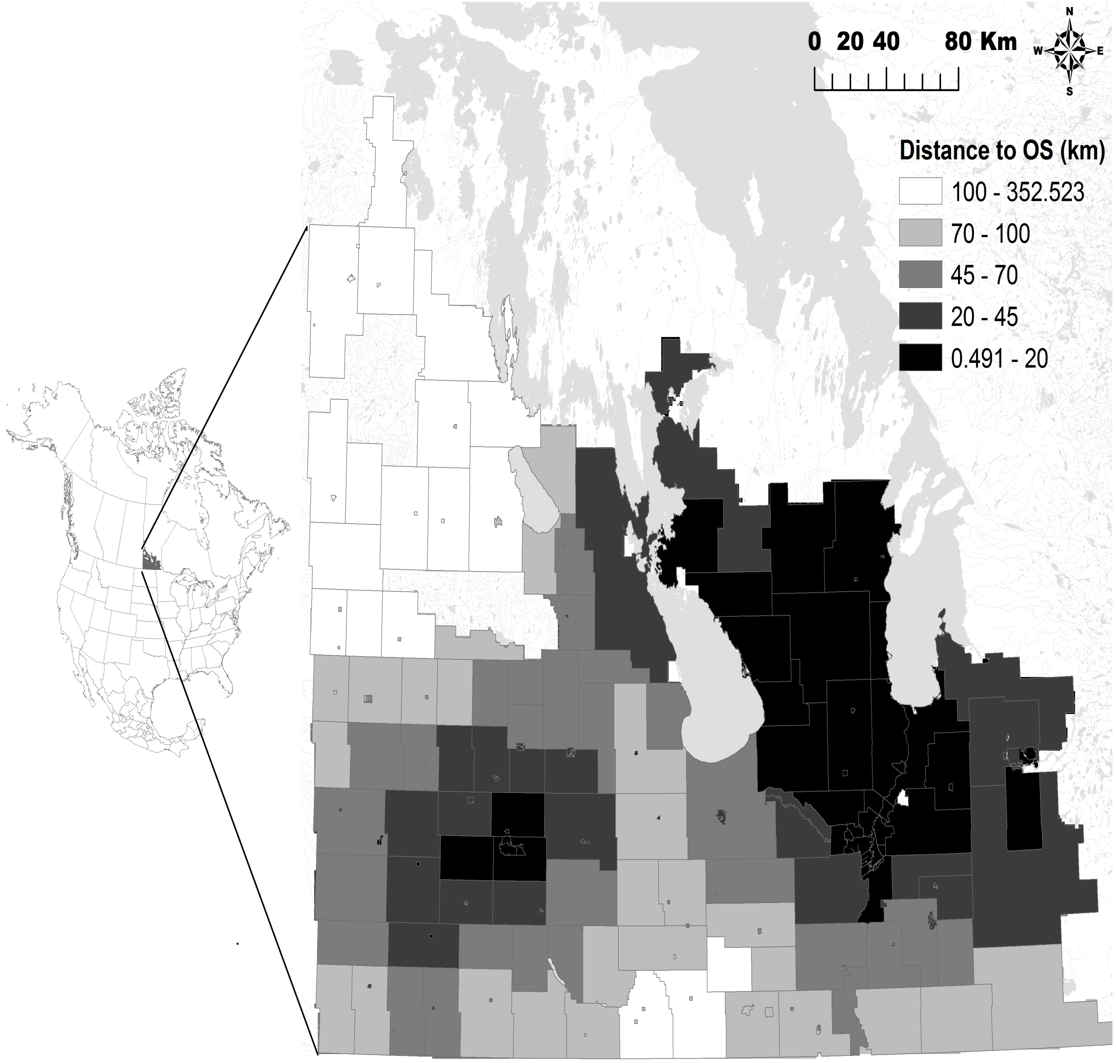

Figure 4.5: RM mean distance to *O. serotina* source populations

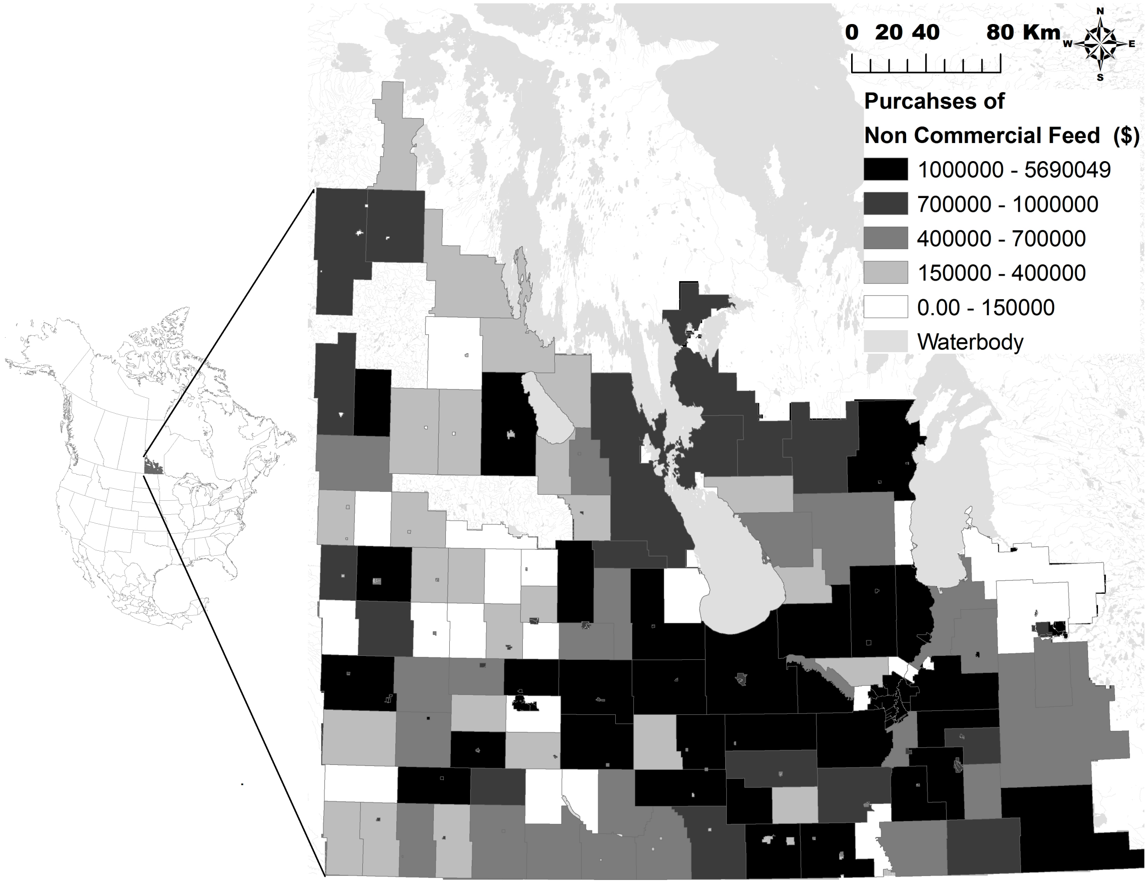

Figure 4.6: RM non-commercial hay sales

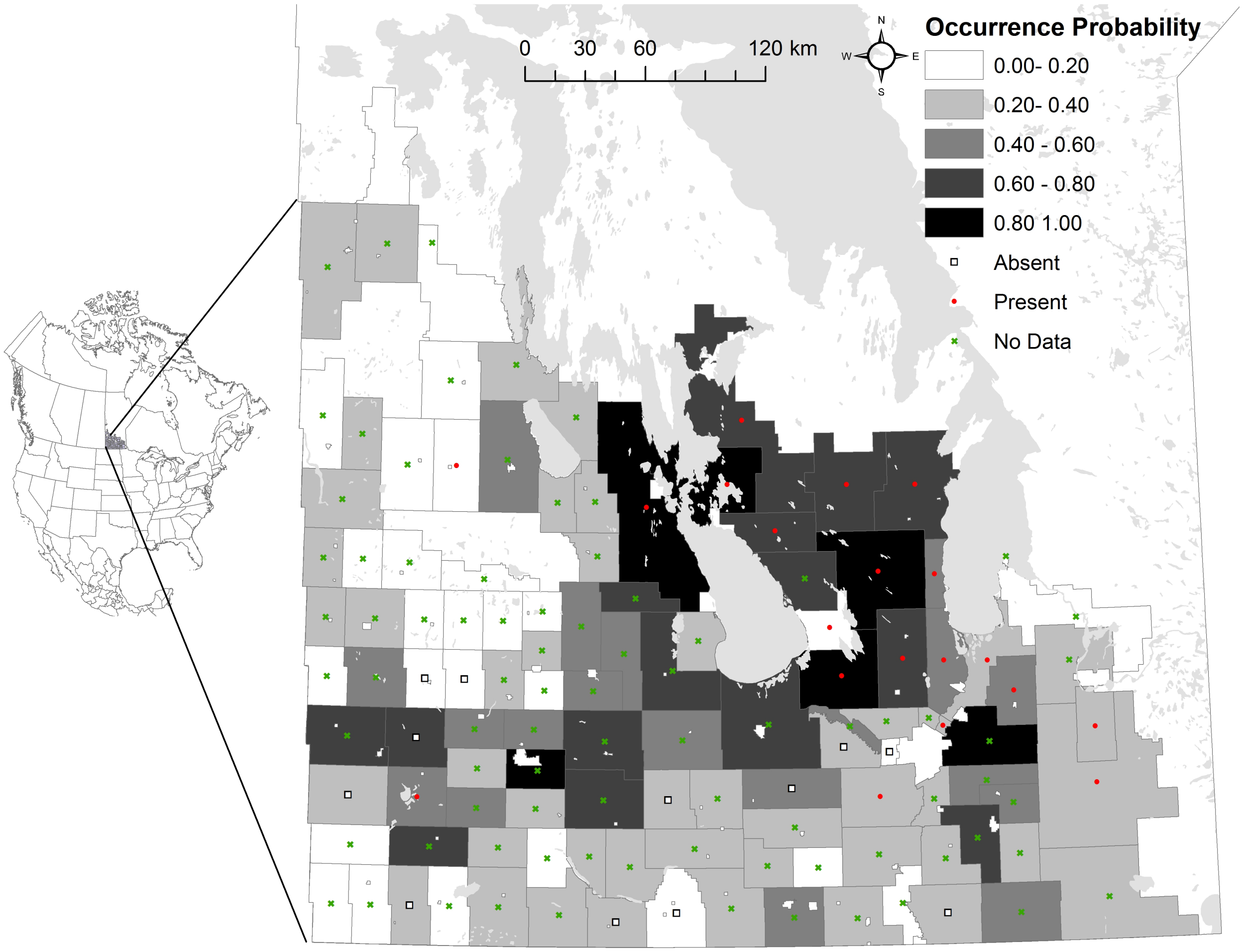

Figure 4.7: Overall risk of *O. serotina* invasion for each RM in Manitoba, including habitat suitability and propagule pressure, with presence and absence data where available.

Results of our risk assessment model for the province of Manitoba indicated that there were several RMs at risk of future *O. serotina* invasion, based both upon the relative abundance of suitable habitat and the probability of propagule introduction. Not surprisingly many of the areas at greatest risk are within the Interlake region of south-central Manitoba (Figure 4.7). While there are already infestations in this region, there is still considerable potential for *O. serotina* to become established at new locations. Some other areas of the province also at risk were the RMs situated on the western edge of Lake Manitoba, some parts of southwestern Manitoba as well as few RMs in the southeastern part of the province (Figure 4.7). Areas with more fertile soils, suited to the cultivation of annual crops such as the Red River Valley, directly south of Winnipeg, and parts of western Manitoba were at relatively low risk of future invasion (Figure 4.7). These areas lack suitable habitat and thus are at low risk even when in relative close proximity to source populations.

4.5 Discussion

As is commonly the case with invasive alien species (IAS) (Hobbs 2000, McNeely 2001), our results showed that human activities were closely linked to the invasion success of *O. serotina*. Anthropogenic land cover variables and proximity to human alterations to the natural hydrological cycle, such as ditches and culverts, were the most important factors associated with *O. serotina* presence. Fields with forage crops, urban or residential areas, pastures, and even native grasslands (through grazing) are subject to relatively high levels of anthropogenic disturbance, which is often connected to the establishment and dispersal of IAS (Byers 2002, Kim 2005). Other studies have linked species invasions to land development, land use history (Lundgren *et al* 2004) agricultural and urban land use and proximity to roadside source populations (Pauchard and Alaback 2004). While human alterations to hydrology, such as drainage ditches and culverts, accelerate drainage in order to reduce in-field flooding, they have also been identified as being important for IAS dispersal, especially in agri-landscapes (Stromberg *et al* 2007*,* Benvenuti 2007).

Our outcomes showed that the presence of *O. serotina* in adjacent roadside habitats was also important. Many studies show that roads act as a conduit, carrying IAS to new areas and enabling these species to colonize surrounding lands (Forman 2003, Pauchard and Alaback 2004). Both farmers and Weed Supervisors indicated that *O. serotina* commonly migrates back and forth between roadside and field habitats. This cross roadside-field dispersal further highlights the importance of propagule pressure, which has been identified as an important mechanism of species invasions in other studies (e.g. D'Antonio *et al* 2001, Rouget and Richardson 2003, Herborg *et al* 2007, Herborg *et al* 2009). Farmers often blamed propagule pressure from roadside infestations as the cause of new populations appearing upon their land, while Weed Supervisors suggested the reverse was also true. Many participants felt that their in field management efforts were futile in light of this propagule pressure. This two-way movement shows how important it is for farmers and Weed Supervisors to coordinate management efforts. A more effective *O. serotina* management strategy might consist of an integrated weed management (IWM) plan, involving a coordinated effort among the various stakeholders.

By incorporating a wide range of variables that emerged from ecological data and local ecological knowledge in our predictive model, we were able to predict invasion risk for the province of Manitoba. However, these outcomes were somewhat limited. Our model was unable to account for fine scale biotic interactions. Our findings show that as a generalist hemiparasite, *O. serotina* is able to invade perennial forages and pasture lands, but it is unclear if particular plant species are ideal hosts, or conversely, if other plant species are resistant to its parasitism. Studies have shown that interactions between hemiparasites and other species within biological communities are complex and substantial enough that they can function as keystone species (Press and Phoenix 2005). Cameron *et* *al* (2006) thus found that both graminoid and legume species serve as suitable hosts for *Rhinanthus minor* (yellow rattle), but two forb species have defense mechanisms that prevent the hemiparasite from accessing their root systems. Other hemiparasites have been found to be more detrimental to preferred host species, thereby influencing competitive interactions within biological communities (Matthies 1996, Joshi *et al* 2000), as well as the overall productivity of host communities, and even enabling the introduction of other exotic species (Joshi *et al* 2000). Clearly, hemiparasites like *O. serotina* can have substantial impacts upon interspecies interactions. Further research is needed to better understand the nature of these biotic interactions taking place between *O. serotina* and other plant species in high diversity communities.

Some dismiss the importance of IAS like *O. serotina* as ruderal species that only pose threats to agricultural fields and other disturbed areas. This arguably reflects an inherent bias towards untrammeled wilderness in North American conservation and ecological research, and a consequent tendency to view human involvement in landscapes as "unnatural" and of less conservation importance (Siipi 2004). Some argue that we need to reconsider this traditional view, which segregates food production from conservation landscapes, and start to develop an "ecoagriculture" model, in which biodiversity preservation is also an explicit goal of rural agricultural systems (Scherr and McNeely 2008). Regardless, the two systems are functionally linked and IAS have the potential to migrate between fields and nearby conservation areas. *O. serotina* is now becoming established within, and in close proximity to, natural habitats (Chapter 3) of conservation importance including high-diversity tallgrass prairie and alvar-like vegetation communities

(Hamel and Foster 2004, Manitoba Conservation Data Centre 2011). Outcomes of related work suggest that *O. serotina* can become established in tallgrass prairies, especially in degraded areas (Kennedy and McLachlan 2008).

Our first measure of propagule pressure, distance to nearest source population, was based upon the most recent available data, including our own field data and the records of Weed Supervisors across the province. It was beyond the scope of this research to conduct detailed field surveys across the entire province, and many RMs in the province do not employ Weed Supervisors and thus are not monitored for IAS. Indeed, we identified several previously unreported occurrences of *O. serotina* through casual observation while traveling through unmonitored RMs. These gaps in information indicate that source populations not accounted for in our model probably do exist. Moreover, these gaps demonstrate that having Weed Supervisors in the field, monitoring for IAS, is a crucial component of EDRR.

Our other measure of propagule pressure was the amount of unconventional feed purchased in each RM, which functioned as a proxy for introduction effort. Unconventional feed purchases are those that are not through a regulated source, but rather directely from farmer to farmer (Statistics Canada 2006). The transport of hay has long been recognized as a vector for IAS (Davies and Sheley 2007) and was identified here as the most important long-range dispersal mechanism for *O. serotina.* However, other anthropogenic forces are also known to transport IAS seeds, such as all terrain vehicles (ATV) (Rooney 2005), farm machinery and municipal road maintenance equipment, such as mowers and graders (Davies and Sheley 2007). Explicitly including these other dispersal vectors in our model was beyond the scope of our study. While participants indicated that these factors also facilitate *O. serotina's* spread, they were seen as facilitating local rather than long-distance dispersal. Local dispersal was indirectly accounted for in our model through the measure of distance to invasion foci.

The demand for feed also varies substantially among years and is affected by weather patterns, further complicating analysis. Unpredictable events, such as droughts or floods, often increase demand, as recently occurred during the spring of 2011. Pastures and perennial forages as far away as 12 km from Lake Manitoba suffered from unprecedented flooding (Manitoba Water Stewardship 2011) and the provincial government declared a state of emergency. Flooding was extensive enough that cattle were temporarily found new pastures and farmers donated hay across the province, all of which will act to facilitate the large-scale distribution of this IAS.

Our outcomes indicate that certain areas in Manitoba have a relatively high risk of future invasion by *O. serotina.* In particular, the Interlake region was at risk, due to its relatively high proportion of hayland, pasture or native grassland (Manitoba Conservation 2002) and the presence of sandy-textured soils that are poorly suited to annual crop production (Podolsky 1986). The threat of future invasion is high in parts of western and southeastern Manitoba, also known for cattle production and associated pasturelands or grasslands (Manitoba Conservation 2002). Although we restricted our analysis to Manitoba, other parts of North America are also at risk. *O. serotina* has been reported in nine of ten

Canadian provinces and six states in northeastern USA (USDA 2011) and it is categorized as a prohibited noxious weed in the province of Alberta (AIPC 2011). Given the potential for negative impacts across these regions, we anticipate that this model will be useful in exploring the potential implications of and priorities for EDRR regarding *O. serotina* in some of these other regions.

4.6 Conclusions and Management Implications

The importance of EDRR in IAS management efforts is increasingly recognized. Like many IAS, once established, *O. serotina* is difficult and costly to manage and has substantial adverse ecological and socio-economic impacts. In the Interlake Weed District, 70% of the weed control budget is devoted to managing this one species and in some areas infestations are so serious that management efforts have been abandoned completely. The overall risk map, resulting from our predictive model and measures of propagule pressure, will be a useful tool for directing future IAS monitoring and management efforts. Rural municipalities identified as being at relatively high risk of future invasion not only have a high proportion of suitable habitat, but are also likely to face propagule pressure. Public education efforts, including species identification tips as well as information regarding potential impacts and management strategies will be most efficient if focused in the highest-risk RMs. Weed Supervisors, farmers and other stakeholders in these areas should be made aware of the threat, survey their lands regularly and aggressively respond to new introductions.

The results of this study highlight the value of incorporating multiple methods to gain a better understanding of the mechanisms of IAS. The spatial patterns of species invasion are influenced by numerous factors, including biotic and abiotic interactions as well as anthropogenic activities. Many previous large-scale studies have focused on the interactions between IAS and abiotic factors such as climate (Peterson 2003, Thuiller *et al* 2005, Chen *et al* 2007). While these studies are useful, particularly for generalizing areas at potential risk across larger scales, they often fail to include the likelihood that the IAS will be introduced into those habitats at risk. Studies that have incorporated measures of introduction risk, or propagule pressure, arguably provide more detailed and useful risk assessments (Rouget and Richardson 2003, Herborg *et al* 2007, Herborg *et al* 2009). In this study, we developed a predictive model that included environmental variables, anthropogenic features as well as measures of propagule pressure. The overall risk map we created thus accounts not only for habitat suitability, but also the likelihood that *O. serotina* will be introduced to the respective RMs across the province of Manitoba.

Our use of LEK played a key role in the generation of these effective risk maps. However, LEK is very rarely incorporated in the IAS literature, to say nothing of *O. serotina*. The use of LEK can play a crucial role in helping bridge gaps in information regarding this recent and under-appreciated IAS (Brook and McLachlan 2008). *O. serotina* has received, and continues to receive, very little attention by researchers; hence there has been little opportunity for evidence to shape EDRR. Most of the government outreach continues to focus on longstanding management responses such as herbicide application and tillage, these of little utility for regions dominated by forages and other perennial crops. The use of LEK helped bridge this gap by suggesting more effective management alternatives that are being explored by farmers (Chapter 3) and generating predictive outcomes that will benefit all stakeholders.

Our incorporation of the LEK of Weed Supervisors and farmers, who have had years and in many cases decades of experience managing the invasive plant *O. serotina,* guided, confirmed and augmented conventional ecological data. It extends other approaches that have incorporated the insights of science-defined experts in risk mapping (e.g. Herborg *et al* 2009, Paini *et al* 2010), by explicitly incorporating farmer knowledge, both in gauging changes in environmental and socio-economic impacts (Chapter 3) and in identifying underlying invasion processes. By addressing these gaps in ecological data, this LEK has played a crucial role in the generation of predictive maps that will be of use for prioritizing monitoring and management responses. These outcomes demonstrate that the combined use of local knowledge and complementary ecological data provides valuable insights into the mechanisms of species invasions, and potential management responses that are unlikely to be attained through either method in isolation.

Importantly, we anticipate that the use of LEK in generating these predictive maps and associated management responses will also result in outcomes that are more likely to resonate with farmers and Weed Supervisors. We have explicitly incorporated these observations, communicated here as quotes from identifiable sources, as outcomes that affirm the importance of experience-based knowledge. Many participants commented that their concerns and experiences had been mostly ignored by all levels of government that continue to downplay the importance of this IAS. In contrast, our outcomes affirm the importance of these farmer experiences and concerns, and will ideally play an important role in informing future decision-making regarding this IAS. The maps form a valuable basis for future engagement with multiple stakeholders. If this outreach is conducted in inclusive and iterative ways, this combination of LEK and ecological data will enable more effective maps to be created in ways that speak to the needs of all those involved.

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Chapter 5: Final Discussion and Research Outcomes

5.1 Framework

Biological invasions represent a considerable threat to biodiversity and society, and, as such, invasion ecology has become an important field of study. Although the value of local ecological knowledge is increasingly recognized as a means of understanding and responding to complex environmental issues, its application in the context of invasive species research has been extremely limited. A recent invader to the province of Manitoba, *Odontites serotina,* has become a great concern in the Interlake region, particularly to farmers. However, little research of any sort has been conducted on this species. Hence its impacts, and factors contributing to its success in the region, remain poorly understood, and even less is known about appropriate management strategies. Through this research, we addressed the gap in the invasive species literature by documenting the local ecological knowledge of farmers and Weed Supervisors to understand and predict future occurrences of the invasive *O. serotina.*

5.2 Research Outcomes

We found that the socio-economic impacts of *Odontites serotina* were severe in affected rural communities. The economic costs related to control efforts were considerable for both Weed Supervisors and farmers, and, for the latter, the costs associated with lost production were even higher. Other effects were socio-cultural in nature. Relationships between community members, and even within families, were strained as a result of this invasive plant. Additionally, there were indirect implications for personal health and well-being. Many of these socio-economic consequences of invasive species tend to be overlooked when these phenomena are considered only from a biological perspective.

The invasion success of *O. serotina* was found to be closely related to human activity. Disturbed elements of these agri-landscapes were most susceptible to infestation and the dispersal of propagules was predominately caused by anthropogenic factors. Additionally, our results elucidated certain demographic trends, associated with rural decline that were facilitating the spread of this invasive plant. An aging rural population, fewer people operating larger farms and more land leased as opposed to owned by farmers, were all factors that contributed to the dispersal, establishment and control of *O. serotina.*

Controlling *O. serotina* infestations proved to be difficult for many participants. In part, this was as a result of its prolific seed production and potential to remain dormant in the seed bank for at least eleven years. The government advocates intensive herbicide application combined with frequent tillage, which is successful in annual crop systems, but not applicable to most farmers in this study. Given the marginal agricultural capacity of the land, annual crops were not sustainable over the long term. Furthermore, because forage crops and pastures are polycultures, including both graminoids and legumes, any applied herbicide damaged non-target, desirable species. As a result, farmers experimented with a wide variety of alternative control methods, ranging from mechanical and manual removal, to vector management, to fertilizer treatments. Methods that showed particular promise were manual removal and the application of compost mulch.

This study was also the first of its kind to incorporate the knowledge of farmers and Weed Supervisors in developing a model to forecast future occurrences of an invasive species. Participants identified factors that explain *O. serotina* presence, such as anthropogenic land cover variables, human alterations to hydrology and soil characteristics, which were used to create our predictive model. By matching important habitat suitability factors with measures of propagule pressure, we generated a map that highlights the relative invasion risk for rural municipalities (RMs) across the province of Manitoba. From this, we determined that the Interlake region, RMs along the western side of Lake Manitoba and some RMs in the south-eastern part of the province have the highest risk of future invasion by *O. serotina.*

5.3 Management Implications

Our research outcomes highlight the limitations of the management approach advocated by government agencies. In areas currently infested by *O. serotina,* as well as those at high risk of future invasion, the prescribed combination of herbicide application and frequent tillage is usually impractical. Other management responses that emerged from this research show potential, but also have their limitations. Application of compost mulch showed excellent promise for *O. serotina* management and is worthy of follow-up research to better understand the extent of and factors underlying its efficacy. Participants with patchy or smaller-scale infestations were able to achieve long-term control with this method, while simultaneously improving forage crop productivity. However, the scarcity of this resource and difficulty hauling it long distances were barriers to expanding this technique across a larger scale. Manual removal of *O. serotina* was a cost-effective, environmentally-friendly means of containing, and in some cases even eradicating, *O. serotina*. However, due to the labour-intensive nature of this response, especially considering the lack of community support in light of rural depopulation trends, the frequency with which farmers have been using this technique has decreased in recent years.

O. serotina management is complex; no single strategy is universally applicable, thus our research suggests that an Intergrated Weed Management (IWM) approach is required to effectively mitigate its impacts. For managing established populations, various combinations of the following management responses: manual removal (hand-plucking); mechanical removal (carefully timed mowing or tillage); compost mulch treatment; and herbicide application, could prove more effective than employing only one method in isolation. For example, although mowing alone had limited control impact, mowing immediately prior to herbicide application enhanced the efficacy of chemical control. Our research also demonstrated the importance of vector management; especially considering that anthropogenic vectors are responsible for most seed dispersal. Thus, any IWM strategy should also consider altering the timing of municipal roadside maintenance activities, such as roadside mowers and graders, so that they do not occur after *O.serotina* has set seed; cleaning farm equipment that has been on infested fields; and, adopting a Weed Free Forage Program to help limit the transport of contaminated hay.

In our study we also found that for future management efforts to be successful, collective action is required. When stakeholders opt out of management activities, they allow their lands to act as a source of propagules for future *O. serotina* invasions, thereby increasing the negative effects and cost of control efforts for others. In the absence of a collaborative management effort, we found that many stakeholders considered controlling *O. serotina* on their land to be futile. Carrying out a coordinated and effective management response among a disparate group of stakeholders may prove to be a difficult task. However, it also presents an opportunity for government agencies, such as Manitoba Agriculture and Food and Rural Initiatives (MAFRI) and Agriculture and Agri-Foods Canada, to play an active role, working together with farmers and Weed Supervisors in an inclusive manner, in developing a community-based management strategy. There is also a chance for the Invasive Species Council of Manitoba (ISCM) and other environmental non-government organizations (ENGOs) to coordinate volunteer events for manual *O. serotina* removal, thus helping stakeholders overcome the labour shortages they face as a result of ongoing rural depopulation.

Early detection and rapid response (EDRR) is also essential to any effective management strategy. EDRR involves both careful monitoring and public outreach, such as providing species identification information and disseminating management information. Ideally, it should involve the collaboration of many stakeholders, including: government agencies; Weed Supervisors; the ISCM and other ENGOs; farmers and other landowners. The risk map that we generated, through the predictive model developed in this study, identifies areas within the province of Manitoba that are at relatively high risk of future invasion by *O. serotina.* This is based upon both the relative abundance of suitable habitat and the likelihood of future introduction. Using this risk map to guide future monitoring and public outreach efforts will make them more focused and efficient.

Some have dismissed the importance of *O. serotina* as a ruderal species, which only threatens agricultural fields and other disturbed areas. The viewpoint that rural agricultural landscapes are of less conservation importance than natural areas is problematic. Given the increased human involvement in landscapes around the world, preserving biodiversity should be a goal even in human-dominated, agricultural systems (Scherr and McNeely 2008). Furthermore, our results suggest that, although *O. serotina* has primarily affected human-dominated landscapes thus far, it could pose a threat to natural areas of conservation importance in the future (Plate 5.1). Occurrences have been recorded within, or in close proximity to, high-diversity tall grass prairie and rare alvar-like vegetation communities. If propagule pressure continues to increase, or if altered disturbance regimes facilitate its establishment, *O. serotina* could become a problem in some of these ecologically sensitive areas. That it is a hemiparasite will likely enable it to invade these important natural habitats, and could in turn facilitate other invasives to become established.

5.4 Future Directions

This study was the first of its kind to document farmer and Weed Supervisor knowledge in the context of invasive alien species. The knowledge of farmers, accrued through a lifetime of observation and informal experimentation, is largely undervalued by scientists and government. Our research outcomes suggest that this form of local ecological knowledge can provide tremendous insights into the invasion process, the socio-economic impacts of invasive species and practical management responses. Hopefully researchers will collaborate with farmers more frequently in the future. There is the potential not only to better understand other invasive species, but indeed, any environmental issues in which farmers have expertise.

We incorporated many environmental variables into developing a model to better understand the spatial dynamics of *O. serotina.* Our results identify factors that are closely related to *O. serotina*'s presence, and in turn, areas that are suited to its future establishment. However, had more resources been available, I would have liked to collect multi-year occurrence data, to understand the temporal dynamics of this invasion as well. This might have provided a better sense of the rate at which it is currently spreading, and hence a better ability to predict when it might reach new areas.

The results of this study also suggest other areas of future research. We documented farmer knowledge with respect to various *O. serotina* management responses. Dave Vasey followed up on some of these management responses for his Honours' research project. Specifically, he compared compost mulch treatment to herbicide control. His research was a valuable contribution and supported the farmer knowledge that emerged from our interviews. There is potential to expand upon his work by examining some of the other responses, such as manual removal, mechanical removal and also Integrated Weed Management, which combines various complementary approaches.

As part of this research project I also wanted to examine *O. serotina*'*s* potential impacts upon natural biological communities. I collected data from four sites where *O. serotina* has recently begun to spread into native prairies and open meadows. The results indicated that *O. serotina* abundance was negatively correlated with diversity measures such as floristic quality and species richness. Had I been able to collect data from the same transects over multiple years, we may have been able to determine whether diverse communities are resistant to invasion and if *O. serotina* facilitates the establishment of other exotics. Further study could also improve our understanding of *O. serotina's* host-parasite interactions in these native plant communities, and how it might influence inter-species competition and community productivity.

With this research, it was our intention to provide a voice for those otherwise marginalized from the research process. Given the fact that the interview participants guided other stages of the research, it is fitting that they also have an opportunity to guide future research. I concluded each interview by asking each participant the direction they would like future *O. serotina* research to take. By far, the most common suggestion was for future researchers to investigate potential biological control agents. This would be an expensive endeavour as it would require many years of research, much of which would occur in *O. serotina's* native range of Europe. Considering that only about 20-30% of biological control agents are successful (Sheppard *et al* 2003) and that temperate annual species have proven the most difficult to control in this way (Chaboudez and Sheppard 1995), I have to question whether this would be the most efficient use of resources. However, I can also understand the participants' perspectives. In some cases, biological control has provided the only effective response to invasive alien species (Meyer and Fourdrigniez 2010), and despite temperate annual species proving difficult to control, there is no clear relationship between a species' biology and its potential for biological control (Charudattan 2005). Biological control could become an important addition to an IWM strategy regarding this invasive, and it might be the most appropriate response for land managers if *O. serotina* becomes a greater threat to natural areas. Now would probably be the best time to start this type of research, before *O. serotina* becomes an even more widespread problem.

Plate 5.1: *O.serotina* observed in native plant communities

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Appendix A: Informed Consent Form

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environment_geography@umanitoba.ca

Department of
Environment and Geography

Informed Consent Form (Individual Interviews)

Research Project Title:	Impacts and Responses to the New Invasive Red Bartsia
Researchers:	Brad Kennedy (Master's Candidate) and Dr. Stephane McLachlan, Department of Environment & Geography, University of Manitoba.
Sponsors:	Manitoba Conservation (SDIF)

This consent form, a copy of which will be left with you for your records and reference, is only part of the process for informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

You are about to participate in a semi-directed interview in order to provide some information on your experiences, opinions and concerns regarding the impacts and responses to the invasive plant Red Bartsia (RB). You will be asked a series of open-ended questions and you will be asked to map any RB populations occurring on your property and to identify possible factors that contribute to the spread of this plant. Finally we will ask you to identify how you have been responding to RB on your farm. Your 'local knowledge' is essential for better understanding the struggles associated with the spread of this invasive plant and is of great potential importance for management and policy making regarding this issue.

You will receive $50 for participating in this interview which will take approximately 90 minutes. During this time, a series of open-ended questions will be used to facilitate conversation with the researchers. We will further ask you to map your experiences with RB using aerial photographs of your farm that we will provide. Your participation in this dialogue is highly encouraged. Please feel free to speak your mind.

An audio recording device will be used during the interview. The information captured will be used to generate a transcript of the proceedings. Should you wish not to be recorded, we will accommodate your concerns.

All of the information that you provide will be kept strictly confidential and will be stored in a locked cabinet, accessible only by the researchers on this project, for the duration of the project (5 years). All audio and originally written records will be destroyed after being transcribed. Your anonymity will be completely maintained through the duration of this research.

The outcomes of this research will include a final report, a graduate thesis, peer reviewed research papers and articles in the farm press. Also, outcomes will likely be posted on the university website. Once we have analyzed the data, we will provide you with a research pamphlet that summarizes the outcomes of this research.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

If you have any questions about the research, please contact Brad Kennedy (204.474.7949) or Dr. Stephane McLachlan (204.474.9316) at the numbers provided, or at their respective email addresses, umkenn01@cc.umanitoba.ca and mclachla@cc.umanitoba.ca

The Joint Faculty Research Ethics Board (JFREB) at the University of Manitoba has approved this research. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Secretariat at 474-7122, or e-mail margaret_bowman@umanitoba.ca. A copy of this consent form has been given to you to keep for your records and reference.

In conclusion, please indicate in the check-off boxes below which of your following you consent to:

☐ no permission to audiotape record for research purposes
or
☐ permission to audiotape record for research purposes, which will later be transcribed and/or analysed

And

☐ permission to release identity in any research outcomes that arise from these interviews
or
☐ no permission to release identity in any research outcomes that arise from these interviews

______________________________ ______________________________
Participant's Signature Date

______________________________ ______________________________
Participant's Printed Name Date

______________________________ ______________________________
Researcher's Signature Date