ASSESSING THE POTENTIAL INVASIVENESS OF CHINESE PLANT SPECIES IN CANADIAN PRAIRIE PROVINCES

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ABSTRACT

Weed seed contaminants in agricultural products from China in recent years have the potential for introducing new invasive plant species. Seeds of 169 weedy species from 39 families were collected from Chinese farmlands. Fifty-eight of these that are currently absent in Canada were evaluated. Two weed risk assessment (WRA) models (modified WRA+ secondary screen tool and weed elsewhere+ modified WRA+ secondary screen tool) rejected all invasive plant species and showed similar accuracy in non-invasvie plant species prediction based on 140 existing alien plant species in Canada, yet the second WRA model took significantly less time to conduct the evaluation. Fifty-five potential invasive species with various negative impacts in Chinese farmlands were rejected to enter Canada by the "weed elsewhere+ modified WRA+ secondary screen tool" model, including eight species that cause significant damage to Chinese farmlands. However, *Anemone rivularis* and *Silene jenisseensis*, which have no negative impacts in China, were also rejected. Seed germination characteristics among 18 Chinese weedy species were found with base temperatures for germination (T_b) varying from -2.5°C to 10.9°C, thermal time requirements to reach 50% germination (θ_{50}) ranging from 23.7 to 209.2°C*Day, and different optimal temperatures for germination, which may facilitate these species to cause different degrees of negative impacts in Canadian prairie provinces. An alien species would have a higher competitive advantage in resource uptake and space occupation than its congeneric with advantageous seed germination characteristics; otherwise it will be less competitive than its congeneric. In addition, plant functional traits that promote invasiveness would make an alien species more invasive. In conclusion, the "weed elsewhere+ modified WRA+ secondary screen tool" model is a fast and highly accurate way to screen out potential invasive species from Chinese environments, and is applicable to other environments with modification. Seed germination characteristics can be used to predict seasonal dynamics of weed seedling populations. The comparison of seed germination characteristics and other plant functional traits between alien plant and its congeneric weed from native areas provides a new way to evaluate the invasive potential of alien plant species.

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LIST OF ABBREVIATIONS

WRA	Weed risk assessment
Modified WRA	Modified Australian weed risk assessment
CFIA	Canadian Food Inspection Agency
TREE	Classification and Regression Tree
θ_{50}	Thermal time requirement for 50% seed germination
T_b	Base temperature for germination
RCBD	Randomized complete block design
T	Temperature
R^2	Coefficient of determination
g	Germination percentage
t_g	Germination time to a given germination percentage
TZ	Tetrazolium chloride
GR	Germination rate
θ	Thermal time
ERH	Enemy release hypothesis
ROC	Receiver operating characteristic
GR	Germination rate
LSD	Least significant difference

1.0 INTRODUCTION

Invasive plant species are recognized to threat native species, communities and ecosystems in the invaded areas (Vitousek *et al*., 1997). They not only reduce the fitness of native species (Molano-Flores, 2014), but also interfere with the production, abundance, and diversity of local plant communities (Gaertner *et al*., 2009; Hejda *et al*., 2009; Powell *et al*., 2011). Ecosystem productivity and pathways of nutrients cycling can be disturbed by plant invasion (Liao *et al*., 2008; Ehrenfeld, 2010). Agroecosystem, one of the major ecosystems in the prairie provinces of Canada, is the most vulnerable ecosystem to plant invasion (Booth *et al*., 2003) and has been severely affected by invasive plant species. Impacts of invasive species on croplands and pasturelands in the Canadian prairie provinces include invasive seed contamination and crop yield loss (CFIA, 2008). Ninety-nine percent of yield losses and herbicide costs in annual crop are caused by invasive plants in Canada (Leeson *et al*., 2005). In addition, the costs of weed control in croplands and pasturelands have been estimated up to $2.2 billion annually on agricultural land base that produce $15 billion of plant products per year (CFIA, 2008). Various vectors are responsible for invasive plant introduction, yet most of invasive plant species were brought into Canada by agricultural production trades in the form of seeds or as fully-grown plants (CFIA, 2008). In recent years, agricultural products from China to Canada have been increasing, and China is regarded to be the second largest source of invasive species introduction into Canadian environments since 2001 (CFIA, 2008). Therefore, to prevent the introduction of invasive plant species from China, it is necessary to screen out Chinese plant species with invasive potential.

The best way to minimize damages by invasive plants is identifying them by weed risk assessment (WRA) models (Keller *et al*., 2007). A WRA model is to evaluate the potential invasiveness of alien plant species via weed status in other parts of world, biological and ecological information of test species (Williamson and Fitter, 1996; Reichard and Hamilton, 1997; Pheloung *et al*., 1999). The WRA model is based on retrospective analysis of plant functional trait disparity between invasive and non-invasive plant species (Williamson and Fitter, 1996; Reichard and Hamilton, 1997; Pheloung *et al*., 1999). Since a successful plant invasion is the result of the interaction of many factors (Kuster *et al*., 2008), WRA models use a combination of variables that promote plant invasion to evaluate the potential invasiveness of

alien plant species (Williamson and Fitter, 1996; Reichard and Hamilton, 1997; Pheloung *et al*., 1999). The performance of WRA models depends on the discriminatory ability of each question to separate invasive from non-invasive plants. Questions with higher discriminatory power indicate that they can separate invasive from non-invasive plants more effectively than those with lower discriminatory power.

There are currently two major WRA models: Classification and Regression Trees model (Reichard and Hamilton, 1997) and Australian WRA model (Pheloung *et al*., 1999). Classification and Regression Trees model predicts plant invasiveness based on questions extracting from a training dataset, and a "best" tree can be attained until a lowest miscalculation rate is found in repeated tests (Reichard and Hamilton, 1997; Caley and Kuhnert, 2006). It usually generates less numbers of questions (around five questions) than the Australian WRA model (Caley and Kuhnert, 2006; Weber *et al*., 2009), which limits its application in other areas (Daehler and Carino, 2000; Krivanek and Pysek, 2006) because of failure to evaluate species lacking questions listed in the tree model. Comparatively, the Australian WRA model predicts potential invasiveness of alien plant species by answering 49 questions related to geographical, biological and ecological information, which leads to a score according to which species are classified as "accepted for import", "evaluate further" or "rejected to entry". The Australian WRA model contains redundant questions as well as questions that are inconsistent with its outcomes (Caley and Kuhnert, 2006; Weber *et al*., 2009). In addition, it takes an average of five hours to evaluate individual plant species (Daehler and Carino, 2000; Kato *et al*., 2006). However, it has a wider range of application areas than the Classification and Regression Trees model (Reichard and Hamilton, 1997; Thuiller *et al*., 2005; Caley and Kuhnert, 2006). Moreover, it provides consistent high accuracy in predicting invasive species in many countries (Pheloung *et al*., 1999; Williams and West, 2000; Daehler *et al*., 2004; Kato *et al*., 2006; Gordon *et al*., 2008; Gasso *et al*., 2010) only with minor alternations for questions related to regional conditions. The Australian WRA model is now officially used to screen out potential invasive plant species from alien areas to entry into Australia. Additionally, its application in Australia over the last 50 years has saved the country up to 1.8 billion Australian dollars (Keller *et al*., 2007). Furthermore, with the application of a secondary screen tool (Daehler *et al*., 2004), the proportion of species in the "evaluate further" category can be reduced.

The "weed elsewhere" question is an important and independent predictor to identify invasive species (Mack, 1996; Reichard and Hamilton, 1997; Daehler *et al*., 2004; Gordon *et al*., 2008), which may facilitate the weed prediction process as compared with the Australian WRA model (McClay *et al*., 2010). Rejmanek (2000) concluded that the success of the Australian WRA model has been largely attributed to its use of the "weed elsewhere" question in determining WRA scores, and meanwhile, high proportion of invasive plant species can be identified by the "weed elsewhere" question in many studies (Rejmanek, 2000; Daehler *et al*., 2004; Gordon *et al*., 2008).

Seed germination characteristics, such as the timing of seed germination, seed dormancy, temperature range for germination, and germination rate/thermal time requirement for germination (Selleck *et al*., 1962; Bough *et al*., 1986; Forcella *et al*., 2000; Steinmaus *et al*., 2000; Raghu and Post, 2008; Cici and Van Acker, 2009), are closely related to plant invasion (Dorado, 2009; Wolkovich and Cleland, 2011). These attributes can be used to evaluate invasive potentials of alien plant species (Ferreras *et al*., 2015). For example, earlier seed germination gives competitive advantage to invasive plants over later germinated species for resources (Dubois and Cheptou, 2012; Vaughn and Young, 2015). Also, rapid germination increases the fitness of invasive plant species (Forcella *et al*., 1986; Schlaepfer *et al*., 2010; Van Kleunen *et al*., 2015). Furthermore, invasive plants with different germination characteristics can cause various degrees of negative impacts in cultivated or natural lands (Dorado, 2009; Wolkovich and Cleland, 2011).

Temperature is one of the most important elements in the environment to control the timing and rate of seed germination (Garcia-Huidobro *et al*., 1982a, b). The effects of temperature on seed germination can be quantified by the thermal time model. Thermal time is the quantity of heat units for plant growth, which is consistent for certain seed populations at different temperature ranges (Fry, 1983). Seed germination characteristics of weedy species can be determined via thermal time model, which has been successfully used to calculate seed germination characteristics of weeds, crops, and vegetables (Garcia-Huidobro *et al*., 1982a, b; Steinmaus *et al*., 2000). Additionally, invasiveness is also associated with taxonomic groups or phylogeny because of trait similarities (Pysek, 1998; Van Kleunen *et al*., 2007). By comparing seed germination characteristics and other functional traits of alien plant species with these of its congeneric native weedy species, invasive potentials can be accurately predicted.

The objectives of this study were:1) to test the applicability of the two WRA models (modified WRA+ secondary screen tool and weed elsewhere+ modified WRA+ secondary screen tool) in the Canadian prairie provinces; 2) to evaluate the potential invasiveness of Chinese plant species using the WRA models; 3) to predict the potential negative impacts of Chinese plant species based on seed germination characteristics and other functional traits; and 4) to evaluate the potential impacts of Chinese weedy species via comparing germination characteristics and other plant functional traits with their congeneric weedy species from Canada.

2.0 LITERATURE REVIEW

2.1 EVALUATING CHARACTERISITICS OF INVASIVE PLANT SPECIES

2.1.1 The Definition of Invasive Plant Species

The definition of invasive plant species is always associated with degradation of local plant communities (Houlahan *et al*., 2004; Hejda *et al*., 2009), crop yield loss (CFIA, 2008), alteration of nutrients cycling (Allison and Vitousek, 2004; Ashton *et al*., 2005), fire regime disturbance (Brooks *et al*., 2004) and interference with human well-being (Pejchar and Mooney, 2009). Generally speaking, an invasive plant species is an alien plant species exerting negative effects on the fitness of native plants, the diversity of native plant communities and nutrients cycling and productivity of native ecosystems (Liao *et al*., 2008; Gaertner *et al*., 2009; Hejda *et al*., 2009; Ehrenfeld, 2010; Powell *et al*., 2011; Molano-Flores, 2014). Humans are considered to be a major vector for the delivery of invasive plant species (Hodkinson and Thompson, 1997; Palumbi, 2001; CFIA, 2008) via the form of a fully-grown plant or seeds. For the assessment purpose, invasive plant species can be categorized into major or minor invasive species based on various degrees of negative impacts in the invaded areas (Pheloung *et al*., 1999; McClay *et al*., 2010).

2.1.2 Plant Invasion Theories

Many theories have been developed to explain the reasoning behind plant invasion phenomena (Davis *et al*., 2000; Ryan *et al*., 2002; Colautti *et al*., 2004; Funk and Vitousek, 2007). For example, the "fluctuating resources" theory describes that invasive plant species are likely to occur in the plant community whenever there is an amount of unused resources (Davis *et al*., 2000). In other words, the environments are likely to be breached by invasive plants as there are available resources, such as light, nutrient and water, and the increase of these resources may be due to environmental surplus, fire, or herbivore disturbance of native vegetation. This theory rests on the fact that the competition strength would be light as a number of unused resources increased. Additionally, some invasive plants are found to display better resources use efficiency than native congeneric species in the low nutrient conditions (Funk and Vitousek, 2007). For example, Funk (2013) concluded that some invasive species in the low resources environments outcompeted its congeners via exhibiting resource conservation traits, such as slow growth, high tissue longevity, and high resource use efficiency.

Also, "enemy release hypothesis" (ERH) indicates that alien plant species, after releasing from the restriction of herbivores and other natural predation (Colautti *et al*., 2004), would increase their chance to become invasive species in new environments (Ryan *et al*., 2002). ERH theory includes biogeographical and community studies: the first focuses on the comparison of original and introduced populations of the same invasive species, whereas the second examines alien species and its congeners occurring in the invaded areas. Currently, one problem is that ERH theory does not clarify whether invasion success is caused by enemy release or reduction (Colautti *et al*., 2004); the another problem is that the natural enemies from the origin areas of invasive species may have a chance to switch hosts by the interaction of abiotic and biotic factors in invaded areas (Pearson and Callaway, 2003). Most ERH studies lack proofs to explain the relationship between "enemy releases" and the abundance and rapid establishment of invasive species (Colautti *et al*., 2004).

Allelopathy is another important factor contributing to plant invasion success (Callaway and Aschehoug, 2000; Hierro and Callaway, 2003), yet the allelopathic effect alone is not regarded as a "unifying theory" in the plant invasion. It is necessary to combine resources (light, nutrient and water) with non-resource mechanisms (allelopathy) to explain plant invasion events, and specify their relative importance based on the environment in which they are studied. Furthermore, invasive plants with phenotypic plasticity are better adapted to the recipient environmental conditions to increase their abundance and impacts in the plant community (Broennimann *et al*., 2007; Lavergne and Molofsky, 2007; Prentis *et al*., 2008). Phenotypic plasticity gives invasive plants competitive advantage to deal with a broader range of environmental conditions by adjusting plant functional traits that confer the invasiveness of alien plant species. Specifically, Matzek (2013) suggested that it was the higher values of functional traits for invasive plants than for non-invasive plants promoting the invasive success over 17 plant functional traits in a group of ten closely related *Pinus* species. Overall, mechanisms that determine plant invasion are various, and plant invasion is closely associated with plant functional traits and environmental invasibility.

2.1.3 The Importance of Climatic Similarity in Plant Invasion

Plant invasive success is also considered to be associated with similarity in climatic conditions between the original and new range of alien plant species (Peterson *et al*., 2003;

Chapman *et al*., 2014). Although plant performance is co-determined by many abiotic and biotic factors, the recipient climatic condition is the most basic requirement for successful establishment of alien plants in invaded areas (Pysek *et al*., 2003), which affects every physiological stage from seed germination, dormancy control to plant growth, phenology and reproduction success (Chapman *et al*., 2014). The term "climate matching" refers to the similarity between native and alien regions based on either a single parameter such as temperature (Chown *et al*., 1998), a suite of climatic variables (Thuiller *et al*., 2005; Richardson and Thuiller 2007), or on indirect measures of climate such as latitude (Maron, 2006; Jimenez *et al*., 2008). Currently, the climate match becomes the central factor grounded in the ecological niche theory, which ecologists use to predict the potential geographic distribution of known invasive species in uninvaded areas (Peterson, 2003). Although there was evidence indicating that some invasive species shift their climatic niches from original climatic type (Gallagher *et al*., 2010), substantial climatic niche shifts were rare among terrestrial invasive plant species (Petitpierre *et al*., 2012).

2.1.4 Plant Functional Traits that Confer Invasiveness

Plant functional traits are morphological, physiological or phenological traits of plant species, such as specific leaf area, plant height, plant size, seed size, tissue nutrient concentrations, flowering period and other traits (Violle *et al*., 2007; Harguindeguy *et al*., 2013). They are closely related to the establishment, survival, competition, impact and fitness of invasive plant species (Van Kleunen *et al*., 2010; Brym *et al*., 2011; Drenovsky *et al*., 2012; Te Beest *et al*., 2015). A growing number of plant functional traits have been testified to promote invasiveness (Rejmanek and Richardson, 1996; Goodwin *et al*., 2001; Van Kleunen and Richardson, 2007; Van Kleunen *et al*., 2010), such as small, short-lived seeds that can germinate without pre-treatment, short juvenile periods and long flowering period, vegetative reproduction, and perfect flowers (Perrins *et al*., 1992, Richardson *et al*., 1994;Thompson *et al*., 1995, Rejmanek and Richardson 1996; Reichard and Hamilton, 1997). Matzek (2013) suggested that higher values of plant functional traits for invasive species than non-invasive species, such as higher leaf area ratio, photosynthetic capacity, photosynthetic nutrient use efficiency and nutrient uptake rates, are attributed to the invasive success. Ferreras *et al*. (2015) found that the alien plant species (*Gleditsia triacanthos*) showed greater germination over time than a co-

occurring species (*Acacia aroma*) that share similar ecological characteristics, which improves the spread of the former into more arid areas.

Additionally, seed germination characteristics can increase invasive plant success (Dorado, 2009; Wolkovich and Cleland, 2011). For example, relatively early germination is positively associated with the potential invasiveness of alien plant species (Seabloom et al., 2003; Pysek and Richardson, 2007; Donohue *et al*., 2010; Dubois and Cheptou, 2012; Vaughn and Young, 2015), whereas a short delay in seed germination timing may result in large differences in final biomass and reproduction (Kelly and Levin, 1997). Seed germination rate also increases the naturalization and fitness of potential invasive plant species (Baker, 1974; Forcella *et al*. 1986; Van Kleunen and Johnson, 2007; Schlaepfer *et al*. 2010; Van Kleunen *et al*., 2015). In particular, Forcella *et al*. (1986) indicated that the invasive ability of *Echium plantagineum* was positively linked to its relatively high rate of germination. The higher rate of germination for the invasive species *Senecio madagascariensis* than for the non-invasive species *S. lautus* contributed to the invasive success of *S. madagascariensis* in Australia (Radford and Cousens, 2000). Moreover, Deering and Young (2006) suggested that relatively high germination rate and early germination timing enabled five annual invasive grasses to outcompete native perennial grasses for space, nutrients and other resources in invaded areas.

Overall, successful plant invasion is co-regulated by the interaction of abiotic and biotic factors rather than any single factor (Lake and Leishaman, 2004; Kuster *et al*., 2008). Also, the same factor may have different weights in the same plant invasion at different stages from initial plant introduction to subsequent invasion (Lloret *et al*., 2005; Dietz and Edwards 2006; Diez *et al*., 2008; Dawson, 2009). For example, invasive plant species would fail to establish in invaded areas if some plant functional traits at one stage are outcompeted by that of native species even if the subsequent trait is superior to that of native species (Seabloom *et al*., 2003). This finding can guide us to restore invasive plant impacts in the invaded areas (Seabloom *et al*., 2003; Vaughn and Young, 2015).

2.2 ASSESSING THE POTENTIAL INVASIVENESS OF ALIEN PLANT SPECIES
2.2.1 Weed Risk Assessment Model

The weed risk assessment (WRA) model was initially developed by using several plant functional traits that promote the invasiveness, to predict invasive plant species. For example,

Rejmanek and Richardson (1996) used discriminant analysis to evaluate the invasive potential of pine species, and concluded that invasive pines can be precisely differentiated from non-invasive ones based on the minimum juvenile period, mean seed mass and mean interval between seed crops. In addition, some traits of invasive plant species, such as perfect flowers, flowering in winter, long fruiting period, chilling requirement for seed germination, and origin in temperate areas, had been identified to promote plant invasiveness and then reversely were used to predict invasive species (Noble, 1989; Richardson *et al*., 1990; Scott and Panetta, 1993; Mack, 1996; Williamson and Fitter, 1996; Reichard and Hamilton, 1997).

Currently, the most widely and frequently used WRA model is the Australian WRA model (Pheloung *et al*.,1999), which uses biological, geographical and ecological information on alien plant species to predict potential invasiveness (Reichard and Hamilton, 1997; Pheloung *et al*., 1999; Brunel *et al*., 2010). The model constitutes 49 questions and can produce a score according to which species are classified as "accepted for import", "evaluate further" or "rejected to entry". The Australian WRA model has some disadvantages: on one hand, it contains questions that are inconsistent with WRA outcomes as well as some redundant questions (Caley and Kuhnert, 2006; Weber *et al*., 2009), and one the other hand, it takes an average of five hours to evaluate individual species (Daehler and Carino, 2000; Kato *et al*., 2006). However, it has a wider application area than other WRA models (Reichard and Hamilton, 1997; Thuiller *et al*., 2005; Caley and Kuhnert, 2006), and the accuracy of this model is consistently high ranging from an average of 80% invasive species rejected (Weber *et al*., 2009) to 90% major invasive species correctly identified (Gordon *et al*., 2008). Furthermore, this WRA model has been widely applied in areas of the world outside Australia and New Zealand for which it was developed (Kato *et al*., 2006; Gordon *et al*., 2008; Nishida *et al*., 2009), and the proportion of species in the "evaluate further" category can be greatly reduced by using a secondary screen tool (Daehler *et al*., 2004).

"Classification and Regression Trees" (Brieman *et al*., 1984) is another WRA model used to predict the invasive potential of alien plant species. Reichard and Hamilton (1997) correctly identified 76% of invasive woody plants using this model. Also, Caley and Kuhnert (2006) found that the classification tree model had a cross-validated sensitivity of 93.6% and specificity of 36.7%. Although "Classification and Regression Trees" model was tested to have a high predictive accuracy in identifying invasive plant species in some studies (Reichard and Hamilton,

1997; Caley and Kuhnert, 2006; Weber *et al*., 2009), it did not perform well in other regions, which may be due to the limited questions listed in the model and ecosystem differences in different regions (Daehler and Carino, 2000; Krivanek and Pysek, 2006).

2.2.2 The Detailed Information of the Australian Weed Risk Assessment Model

The Australian WRA model has been testified as a successful tool for invasive plant species prediction across geographical areas in recent years (Pheloung *et al*., 1999; Daehler *et al*., 2004). This model can identify potential invasive plant species entering into Australian environments. Compared to other models (Daehler and Carino, 2000; Krivanek and Pysek, 2006), the Australian WRA model differentiated invasive species from non-invasive species with a high accuracy (Daehler and Carino 2000; Gordon *et al*., 2008), and has been widely used in many countries (Pheloung *et al*., 1999; Williams and West, 2000; Daehler *et al*., 2004; Kato *et al*., 2006; Gordon *et al*., 2008; Gasso *et al*., 2010).

The accuracy and effectiveness of the Australian WRA model can be tested by identifying groups of non-invasive species and invasive species that are currently present within the test area and comparing the "a priori" designation of "non-invasive species" or "invasive species" with the outcome of "accept" or "reject" by the Australian WRA model. Adjusting the cut-off points that distinguish the outcomes raises the accuracy of prediction about one "a priori" category at the expense of accuracy of predictions for another "a priori" category (Caley and Kuhnert 2006; Pheloung *et al*., 1999).

The Australian WRA model has been implemented into phytosanitary regulations in both Australia and New Zealand. Any plant species brought to either country that has not been previously categorized as "accept" or "reject" need be evaluated before import (Williams and West, 2000). In Australia, using this model on a total of 2,800 species has resulted in the exclusion of 756 species (27%) from 1997 to 2006, whereas 1,484 species (53%) have been allowed the introduction, and 560 species (20%) required further evaluation (Gordon *et al.*, 2008). Recent economic analysis of the WRA model in Australia suggests that implementation was beneficial, and could save that country up to $1.8 billion over 50 years (Keller *et al*., 2007).

2.2.3 Secondary Screen Tool

To reduce the percentage of species identified as a further evaluation, Daehler *et al*. (2004) developed a secondary screen tool, consisting of a small subset of Australian WRA questions in

a decision tree with different questions depending upon species' growth form. For herbs, the questions address whether the species is an agricultural weed, its palatability to grazers and stand density. Running the 24% of test species that had Australia WRA model scores identifying them as evaluate further though this secondary screen tool reduced the species in that category to 8%, with both non-invasive species and minor invasive species reclassified to the "accept" outcome. Tests of this secondary screen tool in the Czech Republic (Krivanek and Pysek, 2006) and Bonin Islands (Kato *et al*., 2006) demonstrated similar reductions in the proportion of species in the evaluate further category (27 to 11% and 26 to 10%, respectively) without decreasing accuracy.

However, one problem with the secondary screen tool is that, for invasive herbaceous plants prediction, the "weeds of cultivated lands" question actually can be used as an independent predictor to reject the potential invasive plant species in the absence of further information (Daehler *et al*., 2004). One reason for this problem is that weeds in the cultivated lands do not always form dense layers on the ground. For example, invasive plant seeds with awned, hooked, sticky, or barbed appendages are more likely to be spread by animals or humans (Sorensen, 1986). In addition, many invasive plant species have evolved to be dispersed by the wind with plumed or winged appendages on seeds (Plummer and Keever, 1963; Burrows, 1986). Also, seeds of some invasive plant species are water dispersed (Thebaud and Debussche, 1991; Kudoh and Whigham, 2001). Another reason for this problem is that some plant species are palatable to livestock yet have a risk to become invasive plants in new environments. For example, white clover (*Trifolium repens*) is one of the most important introduced pasture legumes in North America, but it can displace desirable vegetation if not properly managed (Turkington and Burdon, 1983). Another problem with secondary screen tool is that the question "weeds of cultivated lands" can be switched to "weed elsewhere" question as an independent criteria to identify potential invasive plant species (Mack, 1996; Reichard and Hamilton, 1997; Daehler *et al*., 2004; Gordon *et al*., 2008). Rejmanek (2000) concluded that the success of the Australian WRA model had been largely attributed to its use of the "weed elsewhere" question in determining WRA scores, and 85% of potential invasive plant species had been identified by the "weed elsewhere" question (Rejmanek, 2000). Also, 81% of major invasive plants and 75% of minor invasive plants had been identified by the "weed elsewhere" question alone (Daehler *et al*., 2004). Gordon *et al*. (2008) also found that using the "weed elsewhere" question rejected 92%

(57/62) of invasive species. Therefore, these foundings suggest the "weed elsewhere" question is efficient in detecting invasive plant species.
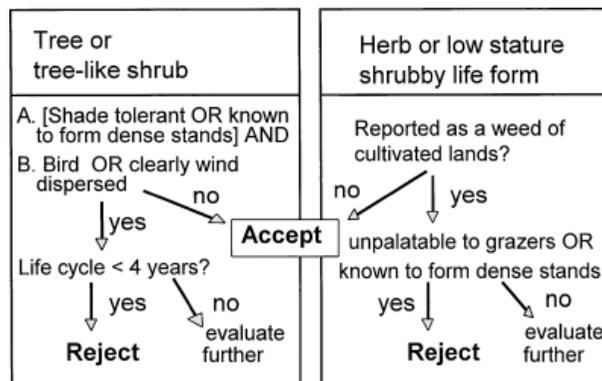
Figure 1.1 A secondary screen tool for species with "further evaluation" scores. Decision tree is used for screening harmful species that had intermediate risk scores between 1 and 6. "Reject" indicates a minor or major invasive species, and "accept" indicates a non-invasive species.

2.2.4 The Distribution of the Major Crop Weedy Species in Chinese Northern Farmlands

The eco-zones in northern China are divided into northeastern humid-temperate, northern warm-temperate, and northern and western plateau-basin of arid or semi-arid climate, in which the climatic condition is similar to that of Canadian prairie provinces. The farmlands in these eco-zones produce wheat, maize, soybean, sunflower, and cotton, and are heavily affected by weed communities such as *Echinochloa-Avena, Fatua-Setaria*, *Digitaria-Descurainia-Galium* and *Avena fatua-Chenopodium* (Qiang, 2002). There are around 1486 weed species belonging to 105 families identified in the cultivated lands of China (Li, 1998). Thirty-seven species (Appendix E) are categorized into the worst weeds, which not only spread widely in northern China and form heavy density, but also cause serious crop yield loss. More importantly, they are hard to eliminate (Qiang, 2002). Menegat (2013) found that *Calystegia hederacea* was one of the most abundant and damaging weeds in the winter wheat of northern China plains and concluded that the top ten most abundant weeds in northern China plains were: 1) *Descurainia sophia*, 2) *Capsella bursa-pastoris*, 3) *Chenopodium ficifolium*, 4) *Calystegia hederacea*, 5) *Chenopodium album*, 6) *Aegilops cylindrica*, 7) *Lithospermum arvense*, 8) *Bromus japonicus*, 9) *Silene conoidea*, and 10) *Avena fatua*. Based on above information, weed species frequently occurring in farmlands of northern China should be closely monitored and prevented from entering Canada.

2.2.5 Taxonomy, Life Form, Life History and Distribution of Invasive Plant Species in Canadian Environments

There are currently 486 out of 1229 alien plant species considered to be weedy or invasive in Canada, most of which belong to 25 families (CFIA, 2008). The major families of invasive alien plants in Canada are Asteraceae (78 species), Poaceae (60 species), Brassicaceae (42 species), Fabaceae (34 species) and Lamiaceae (18 species). Forbs and graminoids take up 83% (405/486) of total invasive plants. In particular, annuals of which 152 are forb and 31 are graminoids. Forty-three invasive forbs are biennial and 150 and 30 are perennial forbs and graminoids, specifically. Manitoba has 257 invasive plant species, Saskatchewan has 249 and Alberta has 225. The provinces with the highest numbers of invasive plant species are Ontario with 431, Quebec with 395 and British Columbia 368 (CFIA, 2008). Based on the distribution of 162 species in Canada, the ecozones most heavily affected by invasive plant species are the Mixedwood Plains, Atlantic Maritime, and Pacific Maritime. High numbers of invasive plant species also occur in the Prairie, Montane Cordillera, and Boreal Shield (CFIA, 2008).

2.3 MODELING SEED GERMINATION CHARACTERISTICS

2.3.1 Seed Germination

Seed germination is a complicated physiological process of initiating growth of a previously quiescent or dormant embryo that is responsive to many environmental signals, including temperature, water potential, light, nitrate, smoke and other factors (Bewley and Black, 1994). Germination is principally managed by hormones such as gibberellic acids (GA) and abscisic acids (ABA), which promote and inhibit this process, respectively (Bewley, 1997; Holdsworth *et al*., 2008). During germination, a series of physiological and genetic events occurs, such as the start of respiration (Bewley and Black, 1994), the restoration of macromolecules (Osborne, 1993), reserve mobilization (Gallardo *et al*., 2001), restart of the cell cycle (Vazquez-Ramos and Sanchez, 2004), and softening of covering structures to allow radicle protrusion (Groot and Karssen, 1987). If a seed fails to complete germination in a specified period under any combination of normal physical environmental factors that otherwise are favorable for its germination, it is defined as dormant.

2.3.2 Temperature and Water Potential Affect Seed Germination

Temperature and water potential are two primary environmental regulators controlling seed germination and dormancy (Bradford, 2002; Baskin and Baskin, 2014). Two distinct effects of temperature have been recognized: the first influences dormancy, and the second determines the germination rate of non-dormant seeds (Bradford, 2002). Seasonal change in temperature mainly determines the loss of primary dormancy and the cycling of secondary dormancy (Hilhorst, 1998). Dormancy in many species can be broken via chilling the imbibed seeds, and the dry after-ripening periods required to break primary dormancy in many species rely on temperature (Baskin and Baskin, 1998). Once the chilling or after-ripening requirements are achieved, the seed is regarded to be non-dormant and either starts to move toward germination or is in a suspended state pending exposure to a remaining trigger (e.g., light, nitrate). The second role of temperature is to control the rate of progress toward completion of germination once a non-dormant seed begins to germinate. This is complicated as the temperature range for germination widens as dormancy is broken and narrows as dormancy is triggered (Benech-Arnold *et al*., 2000).

Water is another important environmental element governing seed dormancy and germination. For most species, germination is characterized with three steps: imbibition of water, with rapid initial water uptake (phase I), followed by a plateau phase with little change in water content (phase II), and a subsequent increase in water content coincident with radicle growth (phase III). Similar to thermal time, the time to germination is related to the magnitude of the differences between the seed water potential and a physiological base or threshold water potential for radicle emergence (Gummerson, 1986).

2.3.3 The Importance of Seed Germination Characteristic in Plant Invasion

Seed germination characteristics, include the timing of seed germination, seed dormancy, temperature range for germination, and germination rate/thermal time requirement for germination (Selleck *et al*., 1962; Bough *et al*., 1986; Forcella *et al*., 2000; Steinmaus *et al*., 2000; Raghu and Post, 2008; Cici and Van Acker, 2009), are closely related to plant invasion (Dorado, 2009; Wolkovich and Cleland, 2011). Seed germination characteristics influences whether a plant outcompetes its surrounding species, or is consumed by herbivores, infected

with diseases, and whether it flowers, reproduces, and matures properly by the end of the growing season (Forcella *et al*., 2000).

The timing of seed germination often determines subsequent plant performance and success (Weiner, 1988). Early seed germination is particularly important when interspecific competition for light is intense as seedling density increases (Miller *et al*., 1994; Seabloom *et al*., 2003). Earlier germination of invasive species than co-occurring native species was found to promote plant invasion (Seabloom *et al*., 2003; Vaughn and Young, 2015). The earlier and higher seedling emergence characteristics confer invasive plant species to naturalize quickly compared with non-invasive species and subsequently accelerate these species to be invasive in new environments (Van Kleunen and Johnson, 2007). A short delay in seed germination can result in large differences in final biomass and reproduction, especially under competitive situations (Ross and Harper, 1972; Venable and Brown, 1988; Rice, 1990; Kelly and Levin, 1997; Dyer *et al*., 2000). Additionally, rapid germination was confirmed to increase the invasive process of alien plant species (Van Kleunen and Johnson, 2007). For example, Forcella *et al*. (1986) indicated that the invasive ability of *Echium plantagineum* was positively linked with its relatively high rate of germination. Also, a higher rate of germination for invasive species *Senecio madagascariensis* than for non-invasive species *S. lautus* contributed to invasive success of *S. madagascariensis* in Australia (Radford and Cousens, 2000). Also, the breadth of temperature ranges for germination increases plant invasion. For example, Pysek and Richardson (2007) concluded that invasive species germinated earlier and better under a wider range of temperature than non-invasive species. Furthermore, Ferreras *et al*. (2015) showed no difference in germination percentages between invasive and native species, but the greater percentage of seed germination over time of the invasive species than that of the native species might be causing the spread of the former, whereas the shorter mean germination time might be hindering its expansion to more arid regions. Finally, with regard to agroecosystems, invasive plant species with the following emergence patterns: early-season emergence, whole-season emergence, and late-season emergence, may cause different degrees negative impacts on croplands and subsequently complicate weed management methods (Dorado, 2009; Lundkvist, 2009).

2.3.4 Modeling Seed Germination

Thermal time (degree-day or hour), the heat sum for specific plant developmental stage, does not vary (Fry, 1983), including germination event for a specific seed subpopulation (Garcia-Huidobro *et al.*, 1982a, b; Ellis *et al.*, 1986). For most seed plants, temperature regulates both seed germination percentage and germination rate (GR). According to Garcia-Huidobro *et al.* (1982a), the thermal time for the percentage germination g at $\theta_{T(g)}$, is:

$$\theta_{T(g)} = (T\text{-}T_b)t_{(g)}$$

where *T* is the actual temperature, T_b is the base temperature for seed germination, and $t_{(g)}$ is the time to germination of *g*. Since *GR* is defined as the inverse of the time to radicle emergence of a specific percentage of the seed population, Equation 1 can be interpreted as:

$$GR_{(g)} = 1/t_{(g)} = (T\text{-}T_b)/\theta_{T(g)}$$

where t_g is the time for germination to reach the fraction *g*, *T* is sub-optimal temperature for germination, T_b is the base temperature or minimum temperature at which *GR*=0, and $\theta_{T(g)}$ is the thermal time to the germination of subpopulation *g*. The relationship between accumulated germination percentage and time follows a sigmoid curve (Garcia-Huidobro *et al.*, 1982a). The GR for specific percentage of seed population is linearly related to the temperature within the sub-optimum temperature range (Bradford, 2002). Therefore, the thermal time or accumulated temperature for germination is a constant among different temperatures for the same subpopulation. The slopes of the line equal to the inverse of the thermal time to germination ($1/\theta_{T(g)}$), which vary among individual seeds in a normal distribution with a mean of $\theta_{T(50)}$ and a standard deviation of $\sigma_{\theta T}$.

The most used method for thermal time model construction is repeated probit analyses developed by Ellis *et al.* (1986). In repeated probit analyses, germination percentages are transformed to probits (normal equivalent deviate units), a linear regression of probits versus log thermal times is calculated, varying the value of T_b until the best fit is obtained (Ellis *et al.*, 1986; Dahal *et al.*, 1990). For a log-normal distribution of thermal time at sub-optimal temperatures, the resulting linear equation is

$$\textit{Probit (g)} = ((T\text{-}T_b)t_g\text{-}\theta_{T(50)})/\sigma_{\theta T}$$

where $(T\text{-}T_b)t_g$=thermal time $\theta_{T(g)}$ or the accumulated degree-days/hours above the minimum temperature (T_b) in a period of time (t) for the 50% subpopulation, and $\sigma_{\theta T}$ is the inverse of the slope or the standard deviation of log thermal times for germination among seeds in the population (Dahal *et al*., 1990). The parameters derived from repeated probit analyses are used to estimate the response time of any specific fraction g of the seed population.

In the repeated probit analyses, finding the optimal range of germination percentages is tricky and laborious due to the repeated analyses with different values of T_b until the residual variance is minimized (Dahal *et al*., 1990). The observed germination percentage ≤90% are usually chosen, since germination data exceeding 90% carry little weight in probit analyses and skew germination response curves (Dahal *et al*., 1990). However, failure of using the original germination data restricts the predictability of seed germination model (Dumur *et al*., 1990). Furthermore, if the range of germination percentages chosen in a repeated probit analysis is not between 0-100%, using median thermal time $\theta_{T(50)}$ as the mean thermal time is problematic.

In recent years classical growth functions, such as Chapman-Richards growth function and Weibull function, have been widely and frequently used to define sigmoid curves (Roman *et al*., 1999; Shrestha *et al*., 1999; Roman *et al*., 2000). The non-linear function is

$$g=a\ (1\text{-}exp\ (\text{-}b\theta_{(g)}))^{\,c}$$

where g is germination percentage, $\theta_{(g)}$ is thermal time for sub-population g, a is the asymptote, b is the rate parameter, and c is the shape parameter. The three parameters, a, b, c, are constants for a seed population.

Germination time course is a sigmoid curve characterized by a lag phase, in which no germination occurs, and an increasing, approximately linear phase leading to an increase in *GR* as the maximum germination percentage is reached (Dumur *et al*., 1990). The Chapman-Richards function fits cumulative seed germination curves well.

3.0 EVALUATING THE POTENTIAL INVASIVENESS OF FIFTY EIGHT CHINESE PLANT SPECIES IN CANADIAN PRAIRIE PROVINCES

3.1 Introduction

Invasive plant species have been causing serious economic losses around the world (Mooney *et al*., 2005). In Canada, plant invasion can cost up to 2.2 billion Canadian dollars annually due to weed control and damage in crops and pastures (CFIA, 2008). Since 2001, China has become one of the major countries exporting agricultural products to Canada. Since agricultural product trade is considered to be one of the primary pathways to bring new potential invasive plant species to Canadian environments upon recent statistic analyses (CFIA, 2008), there is a necessity to prevent the introduction of potential invasive plant species from Chinese farmlands, which may cause serious ecological and agricultural losses to Canadian environments.

Currently, the best way to filter out potential invasive plant species from agricultural products is to use weed risk assessment (WRA) models. Biological, geographical and ecological information of alien plant species played a major role in various WRA models to predict invasiveness of alien plant species, based on plant functional trait disparity between invasive and non-invasive species (Perrins *et al*., 1992; Goodwin *et al*., 1999; Kolar and Lodge, 2002; Van Kleunen *et al*., 2010). Among the various WRA models, the Australian WRA model has been testified as a successful tool for identification of invasive plant species for the past ten years (Pheloung *et al*., 1999; Daehler *et al*., 2004). It can differentiate invasive species from non-invasive species with high accuracy (Daehler and Carino, 2000; Gordon *et al*., 2008) and has been widely applied in many countries (Pheloung *et al*., 1999; Williams and West, 2000; Daehler *et al*., 2004; Kato *et al*., 2006; Gordon *et al*., 2008; Gasso *et al*., 2010).

The Australian WRA model contains 49 questions (Appendix A), relating to biological, ecological and geographical information of alien plant species. In particular, four questions (2.01, 2.04, 4.10 and 8.05) need to be modified to reflect environmental conditions of test areas before application (Williams and West, 2000; Daehler *et al*., 2004; Kato *et al*., 2006; Gordon *et al*., 2008; Gasso *et al*., 2010). Furthermore, the accuracy and efficiency of the Australian WRA model can be tested by identifying groups of non-invasive species and invasive species that are currently present within the test area, and comparing the "a priori" designation of "non-invasive

species", "minor invasive species" or "major invasive species" with the outcome of "accept", "further evaluation" or "reject".

With the application of the modified Australian WRA model and a standard cut-off point (1, 6), the accuracy varies among geographic areas. For example, 77% of invasive species (major and minor invasive species were combined) were correctly rejected, 73% of non-invasive species were correctly accepted and just 10% of the total 158 species needed further evaluation when applying the modified Australian WRA model in Florida (USA) (Gordon *et al*., 2008). The modified Australian WRA model in Hawaii (USA) successfully identified 95% of major invasive species and 66% of non-invasive species, and with 33% of minor invasive species being incorrectly classified as non-invasive species and 24% of total species needing further evaluation (Daehler *et al*., 2004). In Bonin Islands of Japan, 64% of non-invasive species were correctly accepted, 80% of minor invasive species and 93% of major invasive species were correctly rejected, and only 10% of total species needed further evaluation (Kato *et al*., 2006). Furthermore, 80% of minor invasive species and 93% of major invasive species were correctly rejected via the modified WRA model in Czech Republic, 64% of non-invasive species were correctly accepted, and 10% of total species needed further evaluation (Krivanek and Pysek, 2006).

In Canada, McClay *et al*. (2010) concluded that 100% of major invasive species and 86% of minor invasive species were rejected yet 44% of non-invasive species were also rejected, and 18% of total species needed further evaluation with application of the modified Australian WRA model and the standard cut-off point (1, 6). To reduce the proportion of species requiring "further evaluation", Daehler *et al*. (2004) developed a secondary screen tool (Figure 1.1), consisting of four questions in a decision tree. For herbs and small shrubs, the questions address whether the test plant species is an agricultural weed, and information of its palatability to grazers and its dense stand (Daehler *et al*., 2004). Running 24% of total test species that had Australian WRA scores of 1 to 6 (further evaluate) though this secondary screen tool reduced the species in that category to 8%, with both non-invasive species and minor invasive species reclassified to "accept" (Pheloung *et al*., 1999). Using the secondary screen tool in the Czech Republic (Krivanek and Pysek, 2006) and Bonin Islands (Kato *et al*., 2006) demonstrated similar reductions in the proportion of species in the "further evaluation" category (27 to 11% and 26 to 10%, respectively) without sacrifices in accuracy.

The question "weed elsewhere" in the Australian WRA model had been found to be an important predictor to identify potential invasive plants, which emphasizes that test plant species could be weeds in any ecosystems (Mack, 1996; Reichard and Hamilton, 1997; Daehler *et al*., 2004; Gordon *et al*., 2008). Rejmanek (2000) concluded that the success of the Australian WRA model had been largely attributed to its use of the "weed elsewhere" question in determining WRA scores. For example, 85% of potential invasive plant species are identified by this question (Rejmanek, 2000). In addition, 81% of major invasive and 75% of minor invasive plant species are identified when using the "weed elsewhere" question alone (Daehler, 2004). Also, Gordon *et al*. (2008) found that 92% (57/62) of invasive species were correctly rejected by this question.

The objectives of this chapter were: 1) to testify the efficiency and accuracy of two WRA models (modified WRA+ secondary screen tool and weed elsewhere+ modified WRA+ secondary screen tool) in Canadian prairie provinces, and; 2) to assess the potential invasiveness of Chinese weedy species in Canadian prairie provinces. It was hypothesized that the two WRA models can be applied in Canadian prairie provinces with acceptable accuracy and can be used to evaluate potential invasive species from Chinese farmlands.

3.2 Materials and Methods

3.2.1 Chinese Weedy Species Identification and Seed Collection

The list of weedy species to collect was generated based on two sources: 1) Nanjing Agricultural Weed Information System (http://weed.njau.edu.cn) and 2) Weeds of China (Li, 1998). Seeds of 169 plant species (Appendix C) were collected in Northeastern and Northwestern areas of China from July to October of 2010 and 2011, respectively (the province of Jilin, Heilong Jiang, Inner Mongolia, Gansu, Qinghai, and Hebei; Figure 3.1), where agricultural trades with Canada have been increasing in recent years and the climatic condition is similar to that of Canadian prairie provinces.
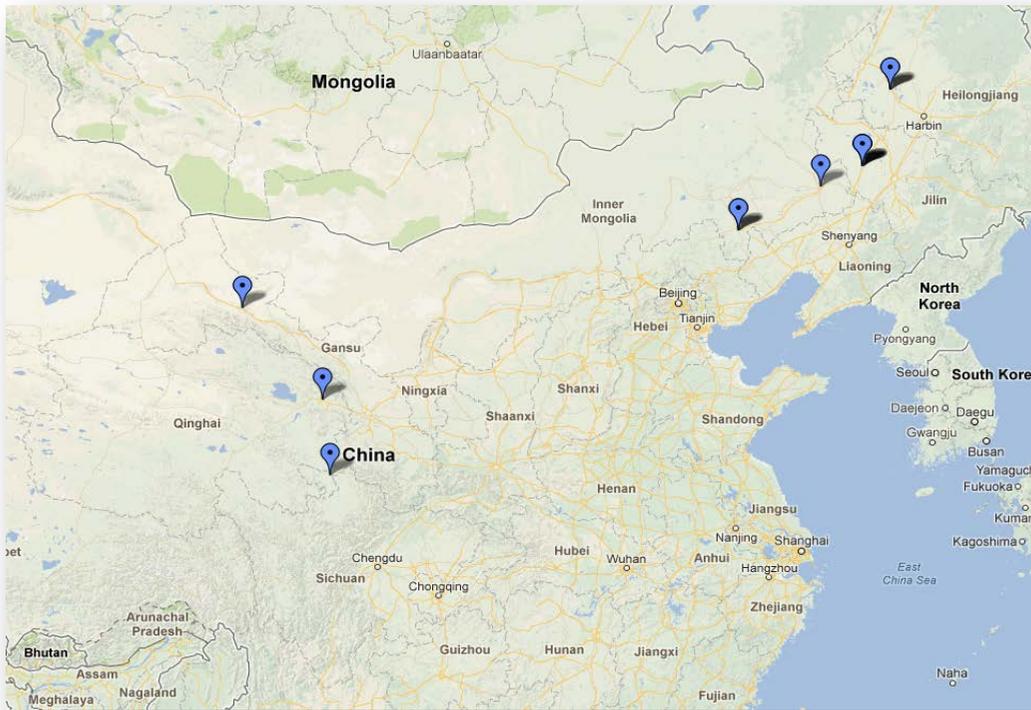
Figure 3.1 Seed collection sites in China

3.2.2 Testing the Accuracy and Efficiency of Two WRA Models under Environmental Conditions of Canadian Prairie Provinces

One hundred and forty herbaceous alien plant species in Canadian environments were selected from: Canadian weed society online database (nine species) (http://www.weedscience.ca); two online databases: ***Beautiful Non-invasive Plants for Your Garden*** (12 species); ***Invasive Alien Plant Species in Canada*** (41 species); and from McClay *et al*. (2010) (78 species). Twelve non-invasive species selected from ***Beautiful Non-invasive Plants for Your Garden*** are recommended as garden flowers and have existed in Canada for a long time. All selected non-invasive species from McClay *et al.* (2010) had been introduced into Canada for more than 50 years, ensuring that they had sufficient time to become invasive species if they have the invasive ability. The "a priori" designation of 140 plant species was categorized based on online information, which was different from the other studies that used experts' opinions to determine the "a priori" designation of test plant species (Pheloung *et al*., 1999; Daehler *et al*., 2004; Gordon *et al*., 2008).

We assigned one of two "a priori" designations to each test plant species: invasive species or non-invasive species, and listed relevant references about negative impacts of each species (Data not show). Invasive species were defined as causing different degrees of negative impacts on croplands, pasturelands, natural areas, and human recreational areas and non-invasive species were defined as having no negative impacts on croplands, pasturelands, natural areas, and human recreational areas (Daehler *et al*., 2004). One hundred and ten species were considered to be invasive species, and 30 were considered to be non-invasive species in Canadian environments (Appendix B). Two WRA models: 1) modified WRA+ secondary screen tool and 2) weed elsewhere+ modified WRA+ secondary screen tool were used to evaluate 140 species. And the accuracy and efficiency of two WRA models were compared.

Four of 49 questions in the Australian WRA were modified to reflect the environmental conditions of Canadian prairie provinces. Question 2.01 "species suited to Australian climates" was modified to "species suited to Canadian prairie provinces climates". The climatic conditions of Canadian prairie provinces are characterized by plant hardiness zone ranging from 0a to 3b (Canada Plant Hardiness Zone, 2000), where most invasive species occur between 1a and 3b (CFIA, 2008). Question 2.04 "native or naturalized in regions with extended dry periods" was modified to "native or naturalized in regions with cold winters and warm summer". Question 4.10 "grows on infertile soils" was modified to "grows on soil types found in Canadian prairie provinces". The common soil types in Canadian prairie provinces are Gray, Dark gray, Black, Dark Brown and Brown soils. Question 8.05 "effective natural enemies present in Australia" was modified to "effective natural enemies present in Canada. In addition, for questions 2.01 and 2.02, we gave maximum scores to all test species as they all fit the environmental conditions of Canadian prairie provinces.

3.2.3 Receiver Operating Characteristic Analyses

The accuracy and efficiency of the modified Australian WRA model can be assessed statistically by Receiver Operating Characteristic (ROC) analyses (DeLong *et al*., 1988), which is used to measure the discriminatory power of the binary classifier system. An ROC curve is created by plotting the portion of true positives (reject invasive species) against the portion of true negatives (accept non-invasive species) across the range of cut-off points on an indicator scale (WRA scores). Species above the cut-off are assigned one outcome (reject), and those

below the cut-off are assigned another (accept). The area under the ROC curve indicates the probability that a randomly chosen positive case (invasive species) will have a higher score than a randomly chosen negative case (non-invasive species) (DeLong *et al*., 1988). Therefore, the closer the area under the curve is to 1, the better the screening tool's ability to seperate invasive species from non-invasive species. If the area under the curve is 0.5, the tool has no ability to discriminate between invasive species and non-invasive species (DeLong *et al*., 1988). ROC analyses require two "a priori" categories, which are invasive species and non-invasive species in study.

3.2.4 Assessing the Potential Invasiveness of Chinese Plant Species

Similarly, one of two "a priori" designations was assigned to 58 Chinese plant species that currently do not exist in Canadian environments: weed or non-weed, depending on online information about their negative impacts in China. For questions 2.01 and 2.02 in the modified Australian WRA model, maximum scores were given to each test species (all fit to Canadian prairie climates) since these species were collected from Chinese farmlands that have similar climatic conditions as those of the Canadian prairie provinces. After these Chinese plant species were evaluated using the modified Australian WRA model, the standard cut-off point (1, 6) was used to differentiate weed species from non-weed species (Appendix D). Fifty-eight Chinese plant species were then assessed using the superior WRA model based on results from the section 3.2.2. Biological, ecological and geographical information of all test species was from online resources and databases.

3.2.5 Data Analysis

Receiver Operating Characteristic (ROC, DeLong *et al*., 1988) analyses were used to measure the discriminatory ability of the modified Australian WRA model to differentiate invasive species from non-invasive species, and demonstrate the trade-offs between correct rejection of invasive species and incorrect rejection of non-invasive species at different cut-off points (Caley and Kuhnert, 2006).

3.3 Results

3.3.1 The Applicability of Modified WRA+ Secondary Screen Tool in Canadian Prairie Provinces

The 110 invasive species had scores ranging from 11 to 38 (25.4 ± 0.6SE), and 30 non-invasive species had scores ranging from -9 to 28 (3.6 ± 1.5SE). The average answered questions were 34 of a total of 49 for 140 test plant species. The average score for each designation was significantly different from each other ($P<0.05$). With the use of standard cut-off point (1, 6), all invasive species and 34% (10/30) of non-invasive species were rejected to enter Canadian environments. Forty-three percent (13/30) of non-invasive species were correctly accepted, and 24% (7/30) of non-invasive species needed further evaluation (Table 3.1).

The rejected non-invasive species included: *Clematis viorna*, *Echinops exaltatus*, *Galanthus nivalis*, *Medicago sativa*, *Molinia caerulea*, *Origanum vulgare*, *Ruta graveolens*, *Vicia lathyroides*, *Iris sibirica*, and *Geranium pusillum.* None of these species was found to have negative impacts in Canadian environments.

Twenty-four percent of non-invasive species that needed further evaluation included: *Rheum palmatum, Eryngium alpinum*, *Penstemon barbatus*, *Sempervivum tectorum*, *Solanum melongena*, *Echinacea purpurea,* and *Lobularia maritima*. After the application of the secondary screen tool (Daehler *et al*., 2004), only one species (*Lobularia maritima*) needed further evaluation, which was recorded as an environmental weed (www.daf.qld.gov.au, accessed, January, 2016) in Australia yet no information about dense stands was found (Table 3.1).

3.3.2 The Applicability of Weed Elsewhere+ Modified WRA+ Secondary Screen Tool in Canadian Prairie Provinces

Using the "weed elsewhere" question as an independent predictor, 99% (109/110) of species that were invasive in Canadian environments as well as outside Canada were rejected (Table 3.2). Only 1% (1/110) of species (*Cichorium intybus*) that was invasive in Canadian environments but has not been recorded as a weed or invasive plant species outside of Canadian environments (Appendix B) tested by the modified Australian WRA model. For non-invasive species, the "weed elsewhere" question incorrectly rejected 20% (6/30) of non-invasive species in Canadian environments yet these species have been recorded as weeds or invasive plant

species in the areas outside Canada. Eighty percent (24/30) of non-invasive species in Canadian environments have been also recorded as non-weeds or non-invasive plant species outside Canada, which were subsequently evaluated by the modified Australian WRA model. No species was accepted into the "accept" category (Table 3.2). Using the modified Australian WRA model and the standard cut-off point (1, 6), the remaining 1% (1/110) of invasive species (*Cichorium intybus*) was identified and rejected to enter Canada. Meanwhile, 43% (13/30) and 40% (12/30) of non-invasive species were accepted and rejected, respectively. In addition, 17% (5/30) of non-invasive species needed further evaluation. Altogether, 60% (18/30) of non-invasive species were correctly accepted when using the modified Australian WRA model alone (Table 3.2). When the secondary screen tool was applied, no non-invasive species needed further evaluation.

Table 3.1 Percent within each "a priori" category of invasive species or non-invasive species species with "accept", "evaluate further", or "reject" outcomes using "modified WRA+ secondary screen tool" model for 140 test species in Canadian prairie provinces.

Outcome	The modified WRA		The modified WRA+ secondary screen tool	
	Non-invasive species	Invasive species	Non-invasive species	Invasive species
Accept	43%	0%	63%	0%
Evaluate further	24%	0%	3%	0%
Reject	33%	100%	34%	100%
Total species	100%	100%	100%	100%

Table 3.2 Percent within each "a priori" category of invasive species or non-invasive species with "accept", "evaluate further", or "reject" outcomes using "weed elsewhere+ modified WRA+ secondary screen tool" model for 140 test species in Canadian prairie provinces.

Outcome	Weed elsewhere		Weed elsewhere+ modified WRA		Weed elsewhere+ modified WRA+ secondary screen tool	
	Non-invasive species	Invasive species	Non-invasive species	Invasive species	Non-invasive species	Invasive species
Accept	0%	0%	43%	0%	60%	0%
Evaluate further	80%	1%	17%	0%	0%	0%
Reject	20%	99%	40%	100%	40%	100%
Total species	100%	100%	100%	100%	100%	100%

3.3.3 The Discriminatory Power of the Modified Australian WRA Model to Evaluate 140 Introduced Species from Canadian Environments

The area under ROC curves (0.97±0.02 SE) was significantly different from 0.5 (P<0.05), indicating that the modified Australian WRA model can discriminate invasive species from non-invasive species (0.97±0.02 SE) (Figure 3.2A). Specifically, ROC curves can also be utilized to demonstrate the trade-offs between correct rejections of invasive species and incorrect rejections of non-invasive species at different cut-off points between the "accept" and "reject" outcomes. The lower cut-off points increased the correct rejection of invasive species, but conversely decreased the correct rejection of non-invasive species, although the relationship was not linear. Different cut-off points corresponded to various combinations of rates of correctly rejecting invasive species and incorrectly rejecting non-invasive species. For example, while it achieved a 99% accuracy correctly identifying invasive species, a 17% probability of incorrectly rejecting non-invasive species occurred. This happened if test plant species that received a cut-off point of 11.5 or higher were rejected, and those that received a score below 11.5 were accepted. If the cut-off point rose to 13.5, 98% of invasive species would be correctly rejected, but 7 % of non-invasive species would be incorrectly rejected. Alternatively, increasing the correct rejection rate of invasive species to 100% would require a cut-off point of 10.5, but 17% of non-invasive species would be incorrectly rejected (Figure 3.2A). The value of the area below the diagonal line is 0.5 of the total area, indicating a complete inability to distinguish invasive species from non-invasive species.
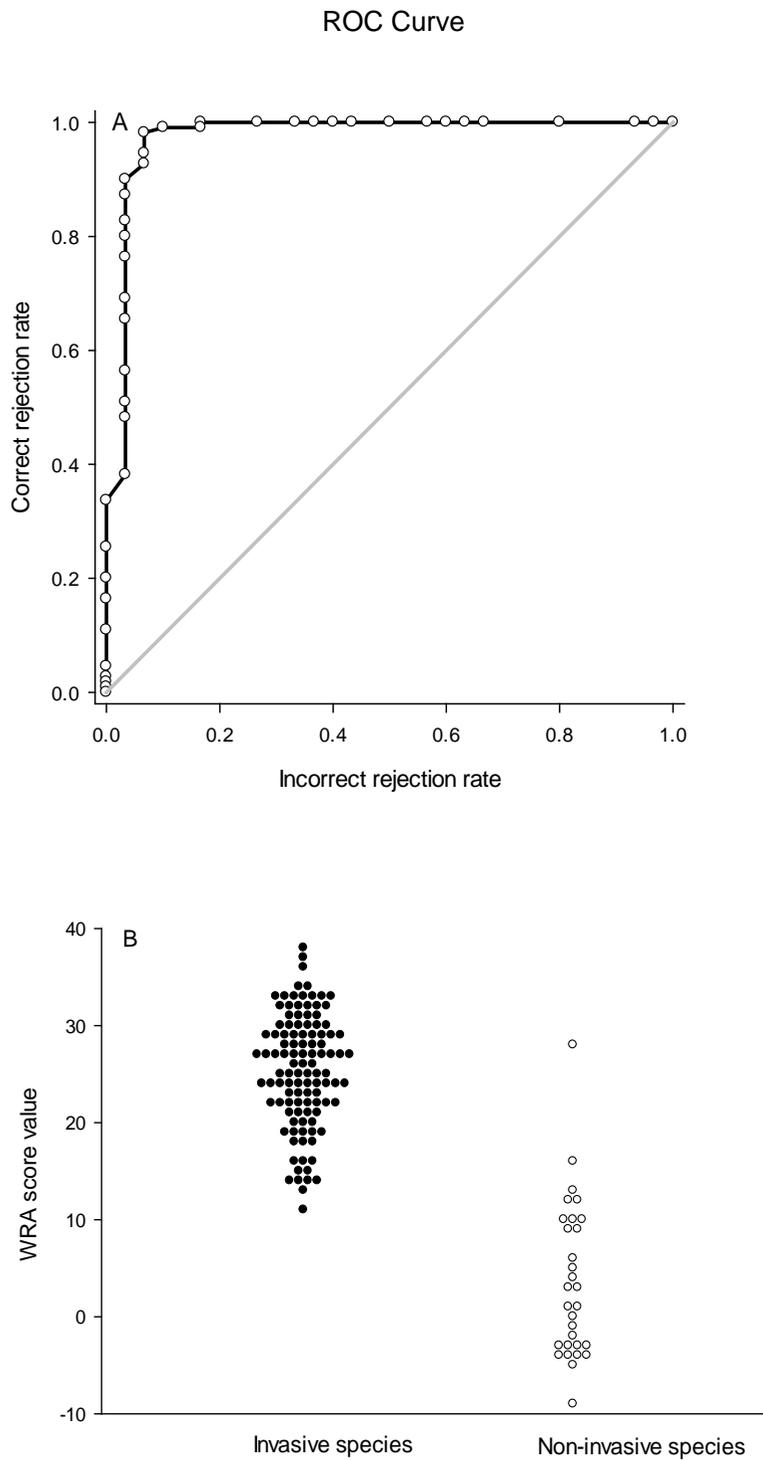
ROC Curve

Figure 3.2 Receiver operating characteristic (ROC) curves showing the discriminatory power of the modified WRA model under climatic conditions of Canadian prairie provinces. One hundred and forty introduced species were evaluated. In this ROC analysis, graphic A is the ROC curves for 140 test species from Canadian environments. In the second graphic B, the black circle represents the modified WRA scores of invasive species; the white circle represents the modified WRA scores of non-invasive species

3.3.4 Assessing the Potential Invasiveness of Chinese Plant Species in Canadian Prairie Provinces

Two "a priori" designations of weed or non-weed were assigned to 58 Chinese plant species based on weedy status in China or areas outside China. Species that have been documented as a weed or an invasive species in any ecosystem were classified as weeds. Otherwise they were classified as non-weeds. For questions 2.01 and 2.02 of the modified Australian WRA model, maximum scores were given (all fit into climatic conditions of Canadian prairie provinces) to these Chinese plant species, because they were collected from Chinese farmlands that have similar climate as Canadian prairie provinces.

Among 58 plant species from Chinese farmlands, 55 were defined as weeds with WRA scores from 6 to 33 (17.0±1.0SE). Three were defined as non-weeds with scores from 6 to 14 (10.3±1.0 SE). The average score for each designation was significantly different from each other (P<0.05). The average answered questions were 30 of total 49 for these species. With the application of standard cut-off point (1, 6), 98% (54/55) of weeds were correctly rejected and 2% (1/55) (*Suaeda glauca*) needed further evaluation (Table 3.3). By contrast, 67% (2/3) of non-weeds (*Anemone rivularis* and *Silene jenisseensis*) were incorrectly rejected and 33% (1/3) (*Dianthus chinensis*) needed further evaluation (Table 3.3). The two rejected non-weeds were *Anemone rivularis* and *Silene jenisseensis*, with WRA scores of 14 and 10, respectively.The third non-weed was *Dianthus chinensis*, whose WRA score was 6.The weed that needed further evaluation was *Suaeda glauca*. Furthermore, when the secondary screen tool was applied, *Dianthus chinensis* was accepted to enter Canada, and *Suaeda glauca* was rejected.

Comparatively, with the application of weed elsewhere+ modified WRA+ secondary screen tool model, all weeds were correctly rejected by the "weed elsewhere" question. Sixty-seven percent of non-weeds (*Anemone rivularis* and *Silene jenisseensis*) were incorrectly rejected and 33% (1/3) of non-weeds (*Dianthus chinensis*) needed further evaluation when using the modified Australian WRA model and standard cut-off point (1, 6). After secondary screen tool was applied, *Dianthus chinensis* was accepted (Table 3.3). It should be noticed that both WRA models denied the introduction of weeds that caused heavy yield losses in Chinese farmlands into Canada (Table 3.5).

Table 3.3 Percent within each "a priori" category of weed or non-weed, of species with "accept", "further evaluation", or "reject" outcomes using "modified WRA+ secondary screen tool" model for 58 Chinese plant species in Canadian prairie provinces.

Outcome	Modified WRA		Modified WRA+ secondary screen tool	
	Non-weed	Weed	Non-weed	Weed
Accept	0%	0%	33%	0%
Evaluate further	33%	2%	0%	0%
Reject	67%	98%	67%	100%
Total species	100%	100%	100%	100%

Table 3.4 Percent within each "a priori" category of weed or non-weed with "accept", "evaluate further", or "reject" outcomes using "weed elsewhere+ modified WRA+ secondary screen tool" model for 58 Chinese plant species in Canadian prairie provinces.

Outcome	Weed elsewhere		Weed elsewhere+ modified WRA		Weed elsewhere+ modified WRA+ secondary screen tool	
	Non-weed	Weed	Non-weed	Weed	Non-weed	Weed
Accept	0%	0%	0%	0%	33%	0%
Evaluate further	100%	0%	33%	0%	0%	0%
Reject	0%	100%	67%	100%	67%	100%
Total species	100%	100%	100%	100%	100%	100%

Table 3.5 Habitats of eight noxious weeds from Chinese farmlands

Major weed	Habitat
Xanthium sibiricum	Cropland, roadside, abandoned lands
Rubia cordifolia	Cropland, countryside, roadside, garden
Polygonum convolvulus	Cropland
Calystegia hederacea	Cropland, roadside, abandoned lands
Erigeron acer	Cropland, grassland
Erodium stephanianum	Cropland, garden, grassland
Chenopodium aristatum	Cropland, roadside, abandoned lands
Digitaria chrysoblephara	Cropland, grassland

3.4 Discussion

3.4.1 The Comparative Efficiency and Accuracy of Two WRA Models

Two WRA models were used to test whether they were applicable in Canadian environments as which were "modified WRA+ secondary screen tool" and "weed elsewhere+ modified WRA+ secondary screen tool". Both models successfully rejected all invasive plants that existed in Canada. By contrast, the first WRA model correctly accepted 63% (19/30) of non-invasive species yet had a high incorrect rejection 34% (10/30) of non-invasive species with 3% (1/30) of non-invasive species needing further evaluation. The second WRA model had a little higher incorrect 40% (12/30) of rejecting non-invasive species. This high accuracy in indentifying invasive species potential was consistent with results from Pheloung *et al*. (1999) and Gordon *et al*. (2008) as minor and major invasive species were combined as invasive species. However, it was significantly greater (P<0.5) than results from similar studies conducted in Hawaii and other Pacific Islands (Daehler *et al*., 2004), Czech Republic (Krivanek and Pysek, 2006) and Bonin Island (Kato *et al*., 2006), which may be due to differences in environmental conditions, dataset composition, or analyses methods in each study (Gordon *et al*., 2008). For example, our dataset focused on herbaceous species that are more likely to invade croplands and pasturelands, and cause serious economic losses in Canadian prairie provinces than invasive woody species (CFIA, 2008). By comparison, other studies often included shrubs and trees, in addition to herbaceous species (Pheloung *et al*., 1999; McClay *et al*., 2010). Invasive mechanisms of herbaceous plants are different from those of trees and shrubs due to differences in life form, seed longevity, seed size and other factors (Brown and Archer, 1999; van Auken, 2000). Additionally, we applied maximum scores to 2.01 and 2.02 questions (Gordon *et al*., 2008) to all test species because they can complete life cycle in environmental conditions of Canadian prairie provinces, while other studies either used plant hardiness zone (McClay *et al*., 2010) or climate matching methods.

Species with various degrees of negative impacts in Canadian environments were correctly rejected by two WRA models. For example, *Artemisia absinthium* is a perennial forb native to temperate regions of Eurasia, which spread throughout Canadian northern areas (Maw *et al*., 1985). This species can invade periodically disturbed areas, such as overgrazed pastures, croplands and hay fields by forming dense stands. Moreover, allelopathic effect of this species was reported to hinder seed germination and prevent seedlings growth of wheat (*Triticum* spp) and common flax (*Linum usitatissimum*) (Chirca and Fabian, 1973). Also, *Sonchus arvensis* is a

perennial herbaceous plant native to Eurasia, which has become a serious invasive plant in croplands of Canadian prairie provinces as well as in the cultivated lands of many countries (Holm *et al.*, 1979). This species was found to reduce wheat yields by 4.5-7% with 3-15 shoots/m^2 (Shashkov *et al.*, 1977), and also to decrease oat yields greatly in Canada (Holm *et al.*, 1997). Some distinctive characteristics of *S. arvensis* are positively related to its invasive ability. For example, it can reproduce via seeds and roots (Stevens, 1924; Derscheid *et al.*, 1961; Lemna and Messersmith, 1990), and a single plant can produce an average of 30 achenes per head and up to 50,000/m^2 (Stevens, 1924; Derscheid and Schultz, 1960; Harris and Shorthouse, 1996). Furthermore, its seeds are equipped with pappus (Peschken, 1984) and can be dispersed by the wind (Stevens, 1924; Dale, 1989; Harris and Shorthouse, 1996). More importantly, seeds of this species can germinate between four days to a maximum seven to nine days after flowering (Derscheid and Schultz, 1960; Kinch and Termunde, 1957; Lemna and Messersmith, 1990), enabling this species to become an early successional pioneer in disturbed areas (Komarova, 1986; Zollinger and Parker, 1999). Moreover, seeds of this species can remain viable for three or more years in the soils (Chepil, 1946). Although this species has better nutritional value than alfalfa (*Medicago sativa*), it is not a palatable feed to grazing animals and infestation of this species can decrease the overall feeding values of forage (Marten *et al.*, 1987). *Agropyron cristatum* (crested wheatgrass) is a perennial grass native to Asia, which is described as a long-lived, cool season, drought tolerant, introduced, and winter hardy grass with an extensive root system (Knowles and Buglass, 1980). Initially, this species was considered for forage use, but in recent years concerns about its ecological impacts have increased. For example, this species was found to dominate roadside ditches in the northern Great Plains (Henderson and Naeth, 2005). In addition, *A. cristatum* is capable of outcompeting native grasses (Schuman and Booth, 1982). Henderson and Naeth (2005) concluded that the abundance of native C$_3$ grasses and forbs in the invaded areas of *A. cristatum* were greatly degraded at population levels, and the dominant cover and seedbank of *A. cristatum* partly decreased plant diversity in the invaded area. The invasive ability of *A. cristatum* may be positively associated with its relatively high tolerance of cold, drought and its suitability to most soils compared with native grass species (Knowles and Buglass, 1980; Smoliak *et al.* 1980). Also, other distinctive characteristics, such as easy establishment and good response to fertilization also contribute to its successful invasion. On top

of that, *A. cristatum* can reduce biomass and growth of native seedlings via disrupting the soil-microbial relationship of native species in the invaded areas (Jordan, 2012).

However, these two WRA models also rejected some species that are not invasive in Canadian environments. The accuracy of non-invasive species prediction in two WRA models was significantly (P<0.5) lower than the results from other geographical areas (Gordon *et al*., 2008). One problem for this low accuracy in non-invasive species prediction is that the modified Australian WRA model has no ability to differentiate invasive plants from non-invasive plants that share overlapping scores, which is an inherited fault (Pheloung *et al*., 1999; Gordon *et al*., 2008; McClay *et al*., 2010). For example, *Ruta graveolens* is a non-invasive species in Canada, but had a WRA score of 16, similar to that of invasive species *Rorippa amphibian*. Similarly, non-invasive species *Origanum vulgare* had a WRA score of 12 which was greater than that of invasive species *Agropyron cristatum* (11). We can adjust the standard cut-off point (1, 6) to accept more non-invasive species. However, the safest solution is to reject all invasive plant species while sacrificing the accuracy of accepting non-invasive plant species.

Another problem is that 20% (6/30) of non-invasive species have been reported as invasive/weed plant species in the areas outside Canada yet are not reported to be invasive in Canada (Table 3.2; Appendix B). These species includes: *Clematis viorna*, *Echinops exaltatus, Geranium pusillum, Molinia caerulea, Sempervivum tectorum* and *Lobularia maritima.* The reasons for this phenomenon are complicated. For example, they may need long time to cause negative impacts. Kowarik (1995) demonstrated that lag time between first introduction and the beginning of invasion is, on average, more than 100 years for trees and shrubs. Daehler (2009) found that the mean lag time between introduction and first evidence of being invasive was 14 years for woody plants and five years for herbaceous plants. In our study, the focus was on herbaceous plant species, and all non-invasive species either are recommended as garden flowers or have existed in Canada for more than 50 years. To determine whether these species will become invasive or not, they need to be monitored in the future. Another reason is that these species may need more propagules to invade into new areas (Lockwood *et al*., 2005) since propagule pressure is considered an essential factor in a successful invasion. The release of large numbers of invasive individuals, or consistent release of invasive individuals into a region to which they are not native enable alien plant species to resist harsh environments and

consequently establish themselves to a certain population size, providing genetic diversity to adapt to new environments (Lockwood *et al.*, 2005).

Even though the predictive accuracy for invasive species and non-invasive species in the two WRA models were similar (Tables 3.1 and 3.2), the efficiency of second WRA model was superior to the first one. All test species needed to go through the modified Australian WRA model to answer as many questions as possible in the first WRA model (Pheloung *et al.*, 1999), which usually takes an average of five or more hours to accomplish individual species evaluation. By contrast, the "weed elsewhere" question in the second WRA model was used as an independent predictor to evaluate the potential invasiveness of alien plant species. It not only reduced time spent greatly (less than 5 minutes) in rejecting species that were invasive in Canada, but also had a high accuracy of 99%. Additionally, the "weed elsewhere" question has been found to keep a consistently high accuracy of predicting invasive species in other studies (Daehler *et al.*, 2004; Gordon *et al.*, 2008). For example, Gordon *et al.* (2008) demonstrated that using "weed elsewhere" question alone rejected 92% (57/62) of invasive species. Also, in Daehler's study (2004) 81% of major invasive plants and 75% of minor invasive plants were identified. Although some species may lack information for the "weed elsewhere" question, this does not affect the predictive accuracy. These non-identified species can be further evaluated using the modified Australian WRA model, and species with different WRA scores classified using the standard cut-off point (1, 6).

The secondary screen tool is useful in accepting alien plant species with intermediate scores between 1 and 6 that are not reported to be weeds in any ecosystem around the world after using the modified Australian WRA model. It has been tested widely as a tool to increase predictive accuracy for invasive species and non-invasive species. For example, this tool has similar reductions for the species with intermediate scores (1 to 6), 27 to 11% and 26 to 10%, respectively, without misclassification in the predictive accuracy for invasive species and non-invasive species (Kato *et al.*, 2006; Krivanek and Pysek, 2006). In our dataset, this tool reduced the proportion of non-invasive species from 24% to 3%, 17% to 0% of non-invasive species in the first and second WRA models, respectively. However, one problem with the secondary screen tool is that for herbaceous plant species evaluation it defines that any plant species can be rejected based on being recorded as a cultivated weed, unpalatable to livestock or known to form dense stands (Daehler *et al.*, 2004). In real quarantine situations, weeds/invasive species

occurring in any ecosystem should be rejected rather than accepted no matter whether they form dense stands and/or are unpalatable to livestock. This is because some cultivated weeds may be palatable to livestock (Turkington and Burdon, 1983) and may not develop dense stands in the field due to seed dispersals (Plummer and Keever, 1963; Burrows, 1986; Thebaud and Debussche, 1991; Kudoh and Whigham, 2001). In addition, some cultivated weeds can switch to environmental weeds or human recreational weeds in novel areas as time goes by (Maron *et al*., 2004). Most importantly, it should be realized that mechanisms of invasive species are more diverse than the formation of dense stand or being unpalatable to livestock (Levine *et al*., 2003).

3.4.2 The Weed Risk Assessment of Chinese Plant Species in Canadian Prairie Provinces

The two WRA models used to evaluate the potential invasiveness of Chinese weedy species had same accuracy of 100% rejection rate of weeds that has been recorded in China or outside China (Table 3.3 and 3.4). In addition, both the modified Australian WRA model (in the first WRA model) and the "weed elsewhere" question (in the second WRA model) independently identified the potential invasive species at a high accuracy (98% and 100%, respectively).

These rejected potential invasive species from Chinese farmlands showed different degrees of negative impacts. For example, eight Chinese cropland noxious weeds have been identified (Table 3.5), which had been recorded to cause significant effects on crop yield loss and crop quality in Chinese farmlands (Li, 1998). *Xanthium sibiricum* is an annual herb occurring in cultivated areas, such as orchards, corn and pulse fields. This species can form dense stands in the disturbed areas and is host for diseases for cotton and sunflower (Li, 1998). The seed of this species has spur that can aid them in dispersal by animals. Most importantly, this species releases chemical compounds that can inhibit crop seed germination and seedling emergence (Xiang *et al*., 2009). *Rubia cordifolia* is a perennial vine with stems up to 10 m long, occurring in croplands and orchards. It can decrease the yield of fruit and crop by competition. In addition, this species can spread by roots, which is an important plant functional trait for invasive ability (Li, 1998). *Polygonum convolvulus* is an annual climbing herb native to Eurasia occurring in the cultivated lands around the world, which is recorded as one of the most abundant weeds in Canadian prairie provinces. A single plant of this species can produce more than 10,000 seeds. In addition, the fact that most of seeds are dormant can exert consistent effects on the cultivated lands (Timson, 1966). Furthermore, some weeds that cause minor impacts in China were also

identified by the two WRA models and rejected to enter Canada. For example, *Saussurea amara* is a perennial species and normally has little negative impacts on arable lands. This species usually grows in the areas with pH values from 8.5 to 9.5 (Li, 1998). *Lespedeza dahurica* is a shrub that reproduces only by seeds, and sometimes occurs in orchards (Li, 1998). These minor weeds not only do not have "distinctive undesirable plant functional traits" compared with noxious species listed above, but also cause ignorant negative impacts to cultivated lands, natural lands or human recreational areas. If a species cause negative impacts in any ecosystem in China or areas outside China, it is reasonable to deny the introduction of this plant species into Canadian environments from an ecological perspective.

However, results of two WRA models came with high incorrect rate 67% (2/3) of non-weeds. One possible reason of inaccuracy about non-weed prediction is the limited dataset size. There were only three non-weeds species from Chinese farmlands, two of them were incorrectly rejected (*Anemone rivularis* and *Silene jenisseensis*). They are currently not recorded as invasive/weedy species in China or areas outside China, and have no distinctive undesirable traits that confer plant invasiveness. Another possible reason is involved with the inherited disadvantage of the modified Australian WRA model, which means it can not differentiate weeds from non-weeds that having overlapping WRA scores.

In summary, weed prediction of Chinese plant species was a highly accurate in rejecting 100% of species that are weeds in China, which may become potential invasive plant species in Canadian prairie provinces. Although it is hard to quantify the potential impacts of these identified weeds in Canadian environments due to biogeographical differences in home range (China) and novel range (Canada), weedy statuses of these species in Chinese environments and two WRA models can provide us a guideline to screen out potentially invasive plant species from China.

4.0 MODELING SEED GERMINATION CHARACTERISTICS OF TARTGED CHINESE WEEDY SPECIES

4.1 Introduction

Canadian agriculture suffers great economic losses from exotic plant invasion, and this has accelerated in recent decades due to increased trade with Asia (Colautti *et al*., 2006; CFIA, 2008). Specifically, China has become an important agricultural trade partner with Canada in recent years. One major concern is that weed seeds from Chinese farms will inevitably enter Canadian environments by accompanying grain product shipments, and subsequently cause significant economic and ecological losses.

Herbaceous weeds with diverse seed germination characteristics have high potential to become invasive species in the Canadian prairie provinces (CFIA, 2008; Dorado, 2009). The consequences of plant invasion intensify if alien plant species with distinctive, undesirable traits that promote plant invasiveness are introduced.

Seed germination characteristics, including seed dormancy, base temperature for seed germination (T_b), germination rate and temperature range for germination, play critical roles in potential plant invasion (Forcella et al., 2000; Steinmaus et al., 2000; Raghu and Post, 2008; Cici and van Acker, 2009). Invasive plant species with a variety of germination characteristics can cause many negative impacts on native environments. For example, early germinating invasive species can dominate resource competition that can improve subsequent growth (Seabloom et al., 2003; Pysek and Richardson, 2007; Donohue et al., 2010; Dubois and Cheptou, 2012; Vaughn and Young, 2015). In addition, a relatively high seed germination rate enables invasive species to colonize and establish quickly, subsequently smothering local plant species' growth (Deering and Young, 2006). Moreover, invasive species with different seed dormancy characteristics can establish a seedbank and exert long-term negative impacts on native environments (Bough et al., 1986; Gioria et al., 2012; Presotto et al., 2014). Since seedlings are the most vulnerable to herbicide control or environmental hazards (Marks and Prince, 1981; Jones and Sharitz, 1989; Rice, 1990), understanding seed germination characteristics is essential for the effective control of invasive plant species (Martinez-Ghersa et al., 2000; Bullied et al., 2003; Brownsey et al., 2013).

Temperature is an essential environmental factor controlling both seed germination and dormancy (Roberts, 1988). It also mediates germination rate in non-dormant seeds (Garcia-

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Huidobro et al., 1982a, b). At the same time, seasonal temperature fluctuations determine the loss of primary dormancy in dormant seeds and the induction of secondary dormancy (Hilhorst, 1998).

Due to temperature's influence on plant establishment, another important tool to combat plant invasion is thermal time model. Thermal time is the accumulated heat above a temperature threshold (Fry, 1983). It has been identified as a successful tool to examine base temperature, thermal time requirement and germination course for seed germination or seedling emergence (Bradford, 2002; Graziani, 2009). Seedling emergence of *Avena sterilis* in winter cereal crops was predicted using a thermal time model for better control of this species (Leguizamon et al., 2005). A thermal time model was also used to predict the seedling emergence of *Papaver rhoeas* in cereal fields, and explained 91% of the variation of seedling emergence observed in the field (Izquierdo et al., 2009). Dorado (2009) categorized the timing of weed seedling emergence in cultivated fields into three types: early-season, whole-season and late-season emergence using thermal time requirements.

Thermal time models have three fundamental assumptions: first, seeds do not germinate below the base temperature (T_b); second, below the optimum temperature, germination rate varies linearly with temperature (Labouriau 1970; Bierhuizen and Wagenvoort, 1974), and finally, T_b is constant for a particular seed population (Garcia-Huidobro et al., 1982a, b; Gummerson, 1986).

The objectives of our research were: 1) to determine the T_b and θ_{50} for germination of selected Chinese weedy species and congeneric pairs from China and Canada; 2) to evaluate the potential invasive ability of Chinese weedy species based on analyses of their germination characteristics, and; 3) to determine the potential impacts of Chinese weeds by comparing their seed germination characteristics and other functional traits that confer invasiveness with that of their congeneric weedy species from Canada. We hypothesized that: 1) T_b and θ_{50} vary among potential invasive species from China, and; 2) seed germination characteristics of Chinese and Canadian weeds in each congeneric pair are different.

4.2 Materials and Methods

4.2.1 Targeted Weed Species Selected for Seed Germination Characteristics Modeling

Forty-seven Chinese weeds were selected (data not shown) based on information of their absence in Canada and invasive characteristics in areas outside Canada were planted at the greenhouse at the University of Saskatchewan from July, 2012 to December, 2012 for seed increase. After maturation, seeds were collected and then stored in the freezer (<-20ºC) for further experimental use.

Nineteen Chinese weedy species with various modified WRA scores (58 plant species pool, Appendix D) were selected for a seed germination test based on seed availability. Meanwhile, five Canadian weedy species were chosen to pair with five Chinese weedy species from the 58 plant species to predict potential negative impacts of these Chinese weedy species in Canadian environments (Table 4.1; Appendix D). A germination test was not conducted for the Chinese weedy species *Aeluropus pungens* due to a shortage of seeds.

Table 4.1 Five weed pairs selected for comparative seed germination tests

Weeds from China	Paired weeds from Canada
Rumex patientia	*Rumex crispus*
Artemisia lavandulaefolia	*Artemisia biennis*
Chenopodium aristatum	*Chenopodium album*
Plantago asiatica	*Plantago major*
Elymus sibiricus	*Elymus repens*

4.2.2 Seed Germination Test

Germination tests were conducted in the Phytotron of the College of Agriculture and Bioresources, University of Saskatchewan, Saskatoon, Canada. We imposed five temperature treatments (0/10, 5/15, 10/20, 15/25 and 20/30 °C) with 12/12 h light/darkness. A randomized complete block design (RCBD) was used with eight replicates at weekly intervals. Imposed temperatures were randomly allocated to growth chambers (one chamber for each temperature treatment).

For each replicate, 50 seeds were imbibed on top of two layers of filter paper (VWR) in 9 cm plastic petri dishes (Phoenix Biomedical Company). The filter paper was moistened with 4-5mL distilled water then petri dishes were enclosed and sealed in clear plastic bags to reduce water evaporation. Seeds were sprayed with 0.05% benomyl solution whenever there was

microbial contamination during incubation. Germinated seeds were counted and removed at 24 hour intervals. Seeds with coleoptiles greater than 2 mm were considered to have germinated and germination tests were terminated if no seeds germinated for 14 consecutive days. Distilled water was added if necessary to keep the filter paper wet.

Additionally, five Chinese weedy species were found to have physiological dormancy and were subjected to dormancy treatment expect for *Aeluropus pungens* which had a shortage of seeds. The remaining four species were chilled at 5°C in darkness for 30 days, and then put into five separate temperature chambers that were set at 0/10, 5/15, 10/20, 15/25 and 20/30°C (12/12h, darkness/light) in a RCBD.

4.2.3 Data Analysis

The Chapman-Richards growth function was used to construct a germination time course curve for each species at each temperature regime (Richards, 1959; Lee, 2002). The Chapman-Richards formula takes the following form:

$$g = a(1 - exp(-bt))^c$$

where, g=seed germination percentage, t=time, a=the asymptote, b=the rate parameter, and c=the shape parameter and where a, b and c are constants. The germination rate for each subpopulation $g(GR_{(g)})$ was calculated using the reciprocal of germination time $(\frac{1}{t_g})$. The base temperature (T_b) and thermal time requirement of each species were estimated using extrapolation methods (Garcia-Huidobro et al., 1982a). Temperature was treated as the dependent variable and plotted against $GR_{(g)}$. The intercept of the linear regression line was T_b and the linear relationship between temperature T and $GR_{(g)}$ varied among subpopulations by the slope of the regression line, which is equal to thermal time requirement of subpopulations $(\theta_{(g)})$:

$$T = T_b + \theta_{(g)}GR_{(g)} = T_b + \theta_{(g)}(t_{(g)})^{-1}$$

To estimate the common T_b, a linear regression model of T on $GR_{(g)}$ for the available subpopulations with a successive increment of 10% was calculated. Actual recorded temperatures in the growth chambers were averaged over the time required for germination of the subpopulation and used for thermal time modelling. Optimal temperature was identified and

data points not following the linear relationship between $GR_{(g)}$ and temperature at temperatures higher than the optimal temperature were removed (Wang et al., 2005). The thermal time model was constructed when at least 30% germination was reached with each subpopulation contained at least three temperature points.

Total germination data were arcsine square root transformed before subjected to analysis of variance (ANOVA). Shapiro-Wilk test was used to test normality. Treatment means were separated using LSD test at P≤0.05.

4.3 Results

4.3.1 Seed Germination Characteristics of Chinese Weedy Species

Base temperatures (T_b, ℃) varied greatly among 13 Chinese weedy species (Table 4.2). For example, *Rumex patientia* had the lowest T_b of -2.5℃ while *Chenopodium aristatum* had the highest T_b of 10.9℃. Thermal time requirement for the 50% seed population (θ_{50}) also varied among these species. *Thalictrum simplex* had the highest θ_{50} (209.2℃ ∗ Day). By contrast, *Artemisia sieversiana* had the lowest θ_{50} (23.7℃ ∗ Day). Meanwhile, *Rumex patientia, Saussurea amara, Artemisia lavandulaefolia, Artemisia sieversiana, Chloris virgate, Elymus sibiricus* and *Picris japonica* had germination percentage greater than 50% at all five temperature treatments. By comparison, *C. aristatum* had the narrowest temperature ranges for seed germination (Table 4.2).

Table 4.2 Mean total germination (%, mean$\pm SE$), base temperature (T_b), and thermal time requirement for 50% subpopulation germination (θ_{50}) of 13 weedy species from China, five paired weedy species from China and Canada, respectively.

Species	Final germination percentage (%) Temperature (℃)						T_b(℃)	θ_{50} (℃ $*$ Day)
	0/10	5/15	10/20	15/25	20/30	P		
Amethystea caerulea[1]	0±0e	78.3±2.3b	87±2.6a	33.2±3.2c	22.7±2.8d	<0.001	8.5	93.5
Artemisia sieversiana	95±1a	98.3±1a	98.3±1a	97.3±1a	82.3±6b	<0.001	0.2	23.7
Chenopodium acuminatum	50.5±4.4bc	64.3±3.6a	60.7±2.2ab	24.9±2.4d	45.6±5.6c	<0.001	5.3	140.7
Chloris virgate	84.1±6.7a	90.3±2.7a	88.6±1.7a	81.8±4.5a	82.7±5a	0.706	0.7	48.3
Digitaria Chrysoblephara	0±0d	68.5±6.5c	84.3±2.2a	82.1±1.6ab	72.5±4.3bc	<0.001	7.0	45.9
Dracocephalum moldavica	91.3±3b	98.5±1a	98.51a	95.3±3ab	0±0c	<0.001	-1.1	62.5
Incarvillea sinensis	11±6.9b	46.7±4.6b	54.1±7.1b	59.6±4.1b	41.0±4.0a	<0.001	6.0	55.6
Kalimeris integrifolia[1]	12.5±5.7c	55.8±2.9b	60.3±5.2b	68.1±3.4ab	78.9±1.9a	<0.001	6.1	75.8
Picris japonica	66±12.3b	86.9±3.4a	96.4±1.0a	96.4±0.7a	88.9±5.4a	<0.008	4.7	28.1
Plantago depressa	1.8±1d	22.3±7c	66.5±4b	98.8±1a	94.3±3a	<0.001	5.5	56.5
Polygonum convolvulus[1]	4.5±1.1d	38.4±5.1bc	28.9±4.8c	63.8±2.2a	41.7±3b	<0.001	2.9	116.3
Saussurea amara	85.9±3.8b	96.4±2.3a	93.6±3.6ab	85.9±3.4a	72.1±7.2c	<0.001	-0.7	61.9
Thalictrum simplex	64.6±4.7c	46.5±4.1c	80±6.0b	93.8±2.2a	89.5±4.1ab	<0.001	3.2	209.2

	Species	0/10	5/15	10/20	15/25	20/30	P	T_b(℃)	θ_{50} (℃ $*$ Day)
	Artemisia biennis	0±0d	46.1±4c	85.8±2.5b	94.9±2.7a	94.6±4.5a	<0.001	5.6	69.5
	Artemisia lavandulaefolia[2]	86.8±1.8a	85.5±3.9a	84.5±3.8a	85.5±2.6a	89.3±2.9a	0.789	0.2	51.2
	Chenopodium album	0±0d	23.3±3c	38.8±4b	65.9±4a	46.8±4b	<0.001	2.2	89.7
	Chenopodium aristatum[2]	0±0c	0±0c	43.8±6b	85.5±2a	87.3±2a	<0.001	10.9	38.8
	Plantago major	0±0c	1.3±1c	41.3±4b	90.5±1a	94±1a	<0.001	3.4	74.9
Pair	*Plantago asiatica*[12]	100±0a	100±0a	89.5±0b	100±0a	100±0a	<0.001	3.4	34.7
	Elymus repens	0±0c	78±2b	86±1a	87±2a	87±3a	<0.001	0.7	74.1
	Elymus sibiricus[2]	95.9±4.5ab	95.9±1.2ab	99.9±0.5a	93.4±5.0ab	87.0±9.4b	0.160	3.1	75.2
	Rumex crispus	0±0b	98.5 ± 0.5a	98.7±0.5a	99.4±0.5a	99±0.5a	<0.001	6.8	15.0
	Rumex patientia[2]	89.7±5.8b	98.3±1.5a	100±1.0a	99.1±2.5a	76.6±5.1c	<0.001	-2.5	95.9

*Means with different letters within each species and parameter are significantly (P≤0.05) different.
[1]Indicates that four Chinese weedy species had seed dormancy.
[2]Represents Chinese weedy species within each weed species pair.

4.3.2 Seed Germination Characteristics of Chinese Weedy Species with Dormancy

Among the five Chinese weedy species that had seed dormancy, *Amethystea caerulea* had germination percentage lower than 10% under 0/10, 5/15, 10/20, 15/25 and 20/30℃; *Plantago asiatica* had no germination at 5/15℃, but germinated greater than 50% at other temperature treatments (0/10, 10/20, 15/25 and 20/30℃). *Kalimeris integrifolia* had no germination at 0/10, 5/15 and 10/20℃. *Polygonum convolvulus* had germination at 0/10, 5/15 and 10/20℃ yet did not reach up to 20% (Data not shown).

After chilling treatment, *P. convolvulus* had a relatively low T_b of 2.9℃ with a slow germination rate, which was due to that fact that 116.3℃ * Day was required for the 50% seed population to germinate. *Amethystea caerulea* had a relatively high T_b of 8.5℃ along with θ_{50} of 93.5℃ * Day. *Plantago asiatica* had a T_b of 3.4℃ along with a relatively low θ_{50} of 34.7℃ * Day. *Kalimeris integrifolia* had a T_b of 6.1℃ along with θ_{50} of 75.8℃ * Day (Table 4.2). Both *P. asiatica* and *K. integrifolia* had germination percentage greater than 50% at all five temperature treatments except that *K. integrifolia* did not reach 50% at 0/10℃. By contrast, *P. convolvulus* germinated greater than 50% just at 15/25℃. *Amethystea caerulea* had germination percengate greater than 50% only at 5/15 and 10/20℃.

4.3.3 Comparison of Seed Germination Characteristics between Five Congeneric Pairs of Weedy species from Chinese Farmlands and Canadian Environments

None of the five Canadian weedy species germinated at 0/10℃. *Rumex crispus* and *Elymus repen* had germination percentage more than 70% at 5/15, 10/20, 15/25 and 20/30 °C (Table 4.2). *Chenopodium album* had the highest germination percentage of 65.9% at 15/25°C, but did not reach 50% at other temperature treatments. *Elymus repens* had the lowest T_b of 0.7°C, while *R. crispus* had the highest T_b of 6.8°C. *Rumex patientia* had the highest θ_{50} of 89.7℃ ∗ Day.

There was a big contrast in T_b and θ_{50} between the two species within each pair of weedy species except that *Plantago asiatica* and *P. major* had the same T_b of 3.4℃. *Rumex patientia* had the lowest T_b of -2.5℃, while *C. aristatum* had the highest T_b of 10.9℃. *R. patientia* had the highest θ_{50} of 95.9℃ ∗ Day, while *R. crispus* had the lowest θ_{50} of 15℃ ∗ Day (Table 4.2). Both *A. lavandulaefolia* and *A. biennis* had germination percentage greater than 80% at 10/20, 15/25 and 20/30 °C. *Artemisia biennis* did not germinate at 0/10℃ yet had 46.1% germination at 5/15℃. By comparison, *A. lavandulaefolia* had germination percentage greater than 80% at 0/10 and 5/15℃ (Table 4.2)
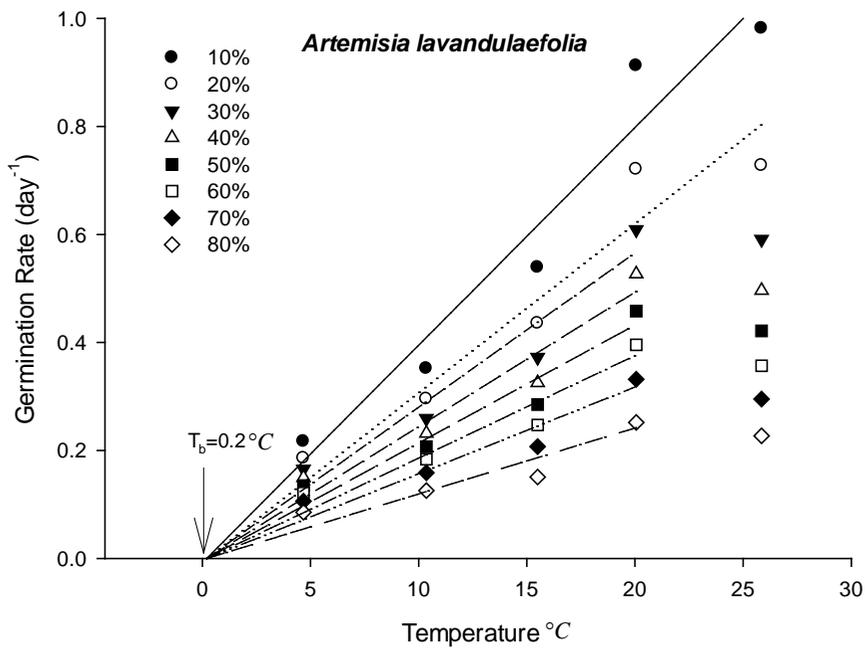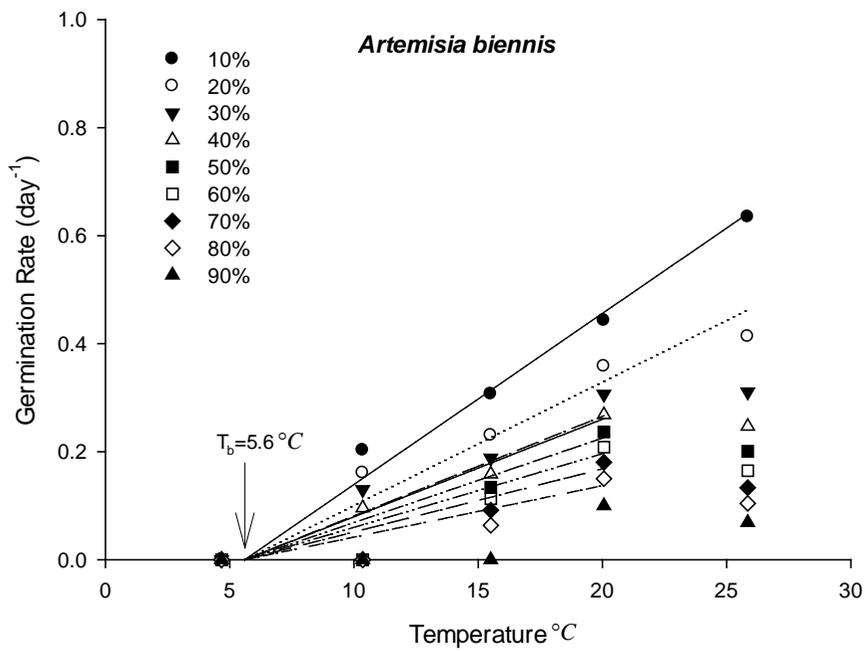
Figure 4.1 Seed germination rate as a function of temperature for paired weedy species *Artemisia lavanduleafolia* and *Artemisia biennis*.
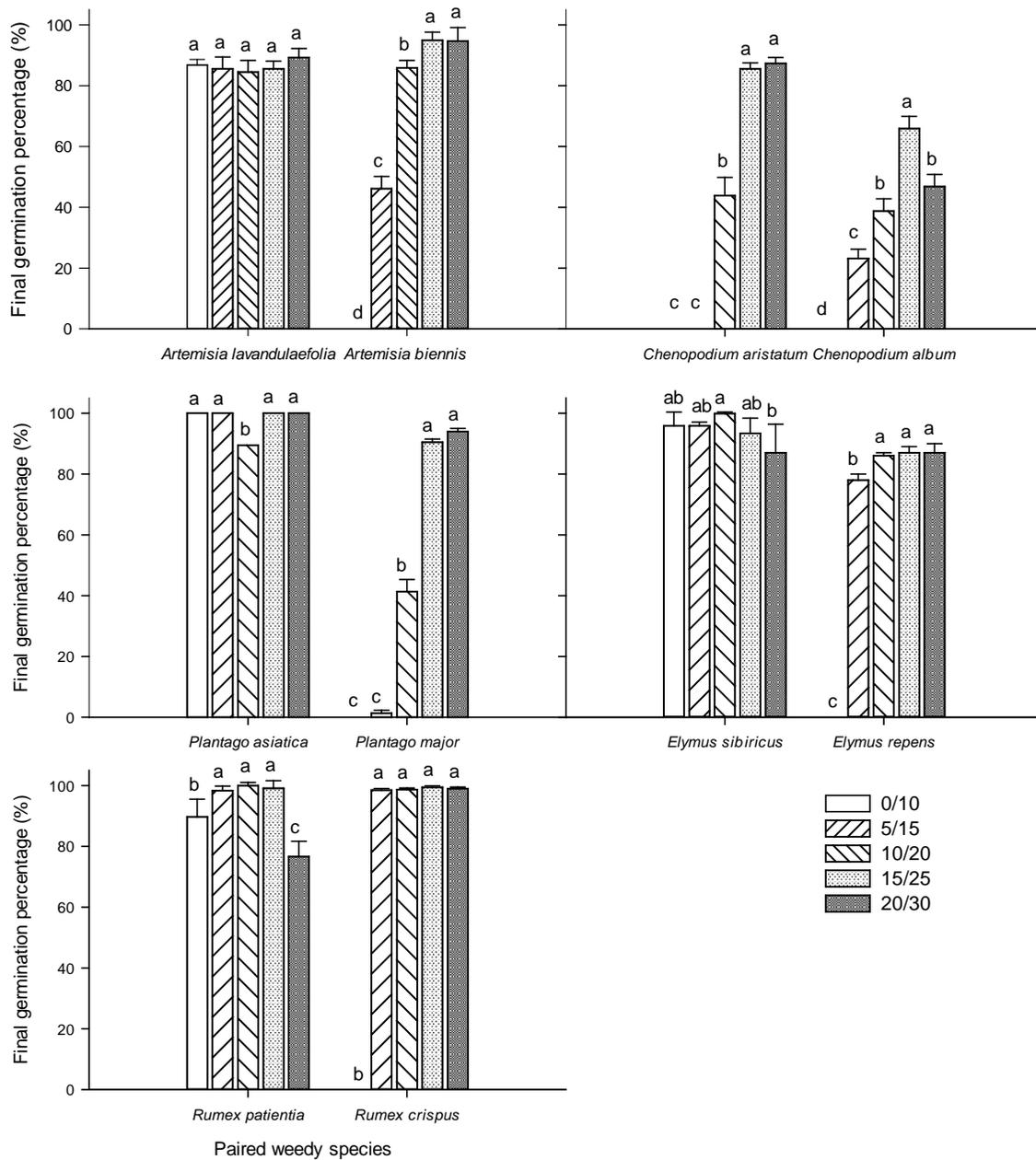
Figure 4.2 Comparison of final seed germination percentage at temperatures of 0/10, 5/15, 10/20, 15/25 and 20/30 °C for five pairs weed species from China and Canada. Means with different letters within each species are significantly different (P≤0.05).

4.4 Discussion

4.4.1 Linking Seed Germination Characteristics to Potential Invasiveness

Seed germination characteristics can be used to evaluate the potential invasive abilities of alien plant species (Ferreras *et al*., 2015), which typically include the timing of seed germination, seed dormancy, temperature range for germination, and germination rate/thermal time requirement for seed germination (Selleck *et al*., 1962; Bough *et al*., 1986; Forcella *et al*., 2000; Steinmaus *et al*., 2000; Raghu and Post, 2008; Cici and van Acker, 2009).

Base temperature varied from -2.5°C to 10.9°C among the 18 Chinese weedy species (Tables 4.2). Comparably, minimum germination temperatures of crops in Canadian prairie provinces vary from 1 to 16 °C (Alberta Agriculture and Forestry, 2010). For example, annual crops such as wheat, barley and oat usually germinate at temperatures close to 4°C, while forage crops alfalfa and sweet clover have lower germination temperatures close to 1°C (Alberta Agriculture and Forestry, 2010). Chinese weedy species that can germinate earlier in the field than crop species in Canadian prairie provinces may gain competitive advantage over crops for space and resources (Tables 4.2; Donohue *et al*., 2010) with longer period of growth and reproduction, increasing their fitness (Verdu and Travese, 2005; Donohue *et al*., 2010; Leiblein-Wild *et al*. 2014). In addition, the fitness of Chinese weedy species can be increased greatly by producing more biomass and having a higher proportion of flowering plants in the invaded areas based on relatively early seed germination (Schlaepfer *et al*., 2010). Therefore, the early germinated Chinese weedy species may cause different levels of damages, similar to the damages caused by some popular weedy species in the Canadian prairies provinces, such as *Kochia scoparia* and *Avena fatua,* which usually degrade crop yield and quality in Canadian prairie provinces partly due to early germination (Willenborg *et al*., 2005; Martinson *et al*., 2007; Schwinghamer and van Acker, 2008; Lewis and Gulden, 2014).

Thermal time requirement is considered to represent the rate of germination, contributing to the increased fitness of invasive plant species (Baker, 1974; Forcella *et al*. 1986; Schlaepfer *et al*. 2010; Van Kleunen *et al*., 2015). Thermal time requirement for the 50% seed population germination differed among the 18 Chinese weedy species (Table 4.2). For example, T_b was similar in Chinese weedy species *Elymus sibiricus* and *Thalictrum simplex* (Table 4.2), but the significantly higher rate of germination for *E. sibiricus* than for *T. simplex* would likely cause

much more negative impacts in Canada (Table 4.2), because a high rate of germination is closely related with invasive success in many invasive plant species cases (Forcella *et al*.,1986; Perrins *et al*. 1993; Radford and Cousens, 2000; Deering and Young, 2006; Van Kleunen and Johnson, 2007). Similarly, *Plantago depressa* may cause more negative impacts than *Chenopodium acuminatum* based on similar base temperatures but a higher rate of germination than *C. acuminatum* (Table 4.2).

The breadth of germination niche under a broader range of temperatures for invasive plant species than non-invasive/native plant species is another factor contributing to successful plant invasion (Forcella *et al*., 1986; Pysek and Richardson, 2007; Cervera and Parra-Tabla, 2009). Chinese weedy species *Dracocephalum moldavica* had no germination at 20/30°C. Also, *Amethystea caerulea* and *Digitaria Chrysoblephara* did not germinate at 0/10°C, and *C. aristatum* had no germination at 0/10 and 5/15°C. By comparison, species such as *Saussurea amara, Artemisia sieversiana*, and *Rumex patientia* were able to germinate at all five temperature treatments (Table 4.2). Chinese weedy species that germinate under a wide range of temperatures may cause more negative impacts than those that germinate only under a narrow range of temperatures in Canadian environments (Forcella *et al*., 1986; Cervera and Parra-Tabla, 2009).

Simply knowing the rate of germination or T_b is not enough to comprehend the potential success of invasive species. It is necessary to combine two factors to evaluate the potential negative impacts of alien plant species in targeted ecosystems (Dorado, 2009; Wolkovich and Cleland, 2011). Base temperature varied from -2.5°C to 10.9°C and along with θ_{50} ranging from 23.7 to 209.2°C*Day among the 18 Chinese weedy species, which indicates that these species show various germination characteristics. For example, *C. aristatum* took less time to accomplish 50% population germination than *R. patientia* at the same temperature treatment. On the other hand, *R. patientia* had a T_b of -2.5°C, significantly lower than 10.9°C in *C. aristatum.* Consequently, *R. patientia* would be considered an earlier germinating weed with longer germination time course compared with *C. aristatum,* which was a later germinating weed with a shorter germination time course, meaning that *R. patientia* can affect crops in the early growing season in the field, and disturb crop growth throughout the whole growing season. In comparison, *C. aristatum* may have less threat to most of crop seedlings at early growing season, and yet would disturb crop growth in the middle of the growing season (Dorado, 2009;

Wolkovich and Cleland, 2011). With above knowledge on seed germination characteristics of Chinese weedy species, effective managements can be applied in invasive species control (Cici and Van Acker, 2009).

Seed dormancy also plays an important role in seedling recruitment and establishment (Van der Valk and Davis, 1978), which can not only assist invasive species to buffer harsh environments and preserve genetic diversity, but also exert continuous negative impacts on the local plant community (Bough *et al*., 1986; Gioria *et al*., 2012). In our study, five Chinese weedy species that have physiological dormancy (Table 4.2) will pose potential long-term negative impacts on local ecosystems once infested. Also, various degrees of dormancy may provide these weedy species with superior competitive advantage over native/non-invasive species due to the difference in germination timing (Moravcova *et al*., 2005; Fisher *et al*., 2009), and seed persistence from dense stands in the field (Brown and Fridley, 2003), which can consequently inhibit the recruitment of native/non-invasive species (Thomsen *et al*., 2006, Fisher *et al*., 2009; French *et al*., 2011). More importantly, seed dormancy enables those dormant Chinese weedy species to exert consistent negative impacts over times on cropland ecosystems via the longevity of invasive species seeds (Bough *et al*., 1986; Thompson *et al*., 1997), especially for these weedy species with prolific seed production (Stevens, 1932; Timson, 1966; Saini *et al*., 1985), such as *Plantago asiatica* and *Polygonum convolvulus*.

Understanding seed germination characteristics of invasive plant species can help us to control them by various efficient ways, such as different herbicide application timings (Monaco et al., 2005; Brosnan et al., 2011), prescribed burning (Murphy and Lusk, 1961) or grazing (DiTomaso et al., 2008). In addition, the method of seeding early established native plant species successfully prevented invasive plant species to establish and spread in native environments (Rose et al., 2001; Seabloom et al., 2003).

It should be noted that seed germination characteristics of a plant species may change when introduced to different geographical areas because of adaption to new environments (Martinez-Ghersa et al., 2000; Tozzi et al., 2014). It is also clear that successful plant invasion is attributed to the interaction of many factors (Kuster et al., 2008), including environmental conditions and plant functional traits, rather than seed germination characteristics alone (Leiblein-Wild et al., 2014; Ferreras et al., 2015).

4.4.2 Evaluate Potential Impacts of Chinese Weedy Species by Comparing Their Seed Germination Characteristics with Congeneric Weedy Species from Canadian Enviroments

Germination characteristics differed between Chinese and Canadian weeds within most congeneric pairs. Chinese weedy species germinated over a wider range of temperatures than the Canadian congeneric, except for *C. album* and *C. aristatum* (Figure 4.2). The different responses to temperature treatments between congeneric weeds in each pair may be due to adaptations to their local environmental conditions (Tozzi et al., 2014).

Base temperature (0.2℃) of the Chinese weedy species *Artemisia lavandulaefolia* was significantly lower than the Canadian weedy congener *A. biennis* (5.6℃), while θ_{50} for *A. lavandulaefolia* was less than *A. biennis*. *Artemisia lavandulaefolia* germinated over a wider range of temperatures from 0/10 to 20/30℃ with final germination up to 80%, whereas *A. biennis* germinated at a temperature range between 5/15 to 20/30℃ with final germination reaching 80% only at temperatures ranging from 10/20 to 20/30℃. *Artemisia biennis* was found to reduce crop yields even at low densities in crops, such as cereals, oilseeds, pulses, and forage crops (Kegode and Darbyshire, 2013). The competitive ability of this species is associated with its dense stands, intermediate seedling emergence, prolific seed production (400,000 to 1 million seeds; Mahoney and Kegode, 2004), and allelopathy (Kegode and Darbyshire, 2013). In contrast, *A. lavandulaefolia* was also found to release chemical compounds to inhibit seedling and root growth of other species in Chinese croplands (Jiang and Zeng, 2006), and has similar seed production to *A. biennis*. Based on information of similar seed production, allelopathic effects and differences in seed germination characteristics between two congeneric weedy species, *A. lavandulaefolia* may have greater effects in Canadian environments than *A. biennis*.

Chinese weedy species, *Plantago asiatica* had physiological dormancy, but its Canadian congener, *P. major* did not. Base temperature of *P. asiatica* was the same as *P. major* at 3.4℃. However, θ_{50} (34.7℃ *day) for *P. asiatica* was significantly lower than θ_{50} (74.9℃ *day) for *P. major*, indicating that *P. asiatica* took less time to reach the 50% seed germination than *P. major* once dormancy was released. In addition, both *P. asiatica* and *P. major* were able to reach a germination percentage greater than 80% under certain temperatures, yet *P. asiatica* had a wider growth temperature range (from 0/10 to 20/30℃) than for *P. major* (ranging from 15/25 to 20/30℃). *Plantago major* already occurs in most provinces of Canada (Hawthorn, 1974). It reproduces primarily by seed, which usually have high longevity and germinate intermittently

throughout the growing season (Toole and Brown, 1946; Hawthorn, 1974). *Plantago asiatica* also reproduces by seeds. Seed dormancy of *P. asiatica* enables it to form seed banks to exert continued negative effects.

Chinese weedy species *Chenopodium aristatum* had a narrower and delayed germination time (T_b of 10.9℃, θ_{50} of 38.8℃ *day) compared with its congener already established in the Canadian prairies, *C. album*, which had a wider and earlier germination (T_b of 2.2℃, θ_{50} of 89.7℃ *day). *C. album* has a world-wide distribution (Bassett and Crompton, 1978) and is one of the ten most important weeds in Saskatchewan (Thomas, 1977). An average sized plant can produce approximately 72,450 seeds (Stevens, 1932), and persist in soil seed bank for over 30 years (Toole and Brown, 1946). Moreover, seeds of this species that produce under long photoperiods (16-17 hours) are more likely to be dormant than those that produce in short photoperiods (8 hours) (Wentland, 1965). This species is toxic to livestock if ingested in large amounts over a short period of time, and its airborne pollen can cause summer hay fever in people (Wodehouse, 1971). Comparatively, *C. aristatum* is a common noxious weed in China with prolific seed production and dense stands (Li, 1998). Based on seed production, longevity, weediness and germination characteristics of these two weedy species, Chinese weedy *C. aristatum* may be less invasive than *C. album*, but its delayed germination may be more problematic for weed control.

The Chinese weedy species *Elymus sibiricus,* has a significantly higher T_b (3.1℃) than the Canadian weedy species *E. repens* (0.7℃) but with similar θ_{50}, indicating that the former has delayed germination. *E. repens* is a noxious weed on the Canadian prairie provinces (Rioux, 1973). More importantly, this species reproduces rhizomatically and an average of 200 shoots can be produced by a single plant (Royer and Dickinson 1999, Whitson et. al. 2000). It forms dense stands, limiting the regeneration of native woody species and interfering with the restoration of native grasslands (Klein, 2011). In addition, *E. repens* can secrete chemical compounds from its shoots and roots, restricting the growth of surrounding plant species (Whitson et al., 2000). *E. sibiricus* can also regrow from rhizomes (Klinkenberg, 2010), and its dense rods layer can restrict seed germination and seedling growth of native plants (Klinkenberg, 2010). However, no evidence suggests that *E. sibiricus* has allelopathic effects. Therefore, *E. sibiricus* may be less damaging than *E. repens*.

Finally, the Chinese weedy species *Rumex patientia* germinated significantly earlier (-2.5℃) than *R. crispus* (6.8℃), but a longer time was needed for *R. patientia* to reach 50% seed

germination (95.9℃ *day) than for *R. crispus* (15℃ *day). *R. crispus* can spread by seeds and root fragments, and a single plant can produce up to 60,000 seeds annually with longevity in the soil seed bank of two to four years or more (Monaco and Cumbo, 1972). *R. patientia* has similar seed production as *R. crispus* (H. Wang personal observation), and it is found in moist environments. Therefore, earlier germinating *R. patientia* with a slow rate of germination may cause greater damage than later and faster germinating Canadian weedy species *R. crispus* in moist areas of Canadian environments.

Overall, seed germination characteristics, as one of the critical phenological stages of plant history (Walck *et al*., 2011; Baskin and Baskin, 2014; Ludewig *et al*., 2014), play a fundamental role in plant invasive success (Seabloom *et al*., 2003; Vaughn and Young, 2015). The invasive potential of alien plant species can be evaluated by comparing its germination characteristic and other plant functional traits with those of its congeneric weed from native areas. Moreover, germination characteristics of invasive species can provide us efficient ways to control invasive infestations in croplands, pasturelands and natural lands (Seabloom *et al*., 2003; Vaughn and Young, 2015).

5.0 GENERAL DISCUSSION AND CONCLUSIONS

Evaluation of potential invasive plant species from China by WRA models is an important way to protect Canadian prairie provinces. This method can not only reduce the risk of introducing potential invasive species into Canada, but also save money in the control of existing invasive species. Both WRA models in this study identified all invasive herbaceous plant species in Canadian environments. Comparing seed germination characteristics and other plant functional traits that confer invasiveness between congeneric weed pair from native and alien environments is a potential new way to evaluate potential negative impacts of alien plant species.

Based on the database of 140 existing alien plant species in Canadian environments, the two WRA models had 100% accuracy of rejecting invasive species, but 63% of non-invasive species was accepted by "modified WRA+ secondary screen tool" model, and 60% of non-invasive species was accepted by "weed elsewhere+ modified WRA+ secondary screen tool" model, respectively. Although results were similar, the efficiency of the second WRA model was higher than the first one. Ninety-nine percent of invasive species that existed in Canada were rejected by the "weed elsewhere" question alone, eliminating the need to be further evaluated by the modified WRA to answer 49 questions. Answering 49 questions usually takes an average of five hours to search for plant geographical, biological or ecological information (Gordon *et al*., 2008), and some of that information is lacking, which may result in misclassification of alien plant species. The only disadvantage of this WRA model is that it incorrectly rejected 20% of non-invasive species present in Canada, which are garden flowers in Canada. For 58 Chinese plant species, the two WRA models had high accuracy of 100% in rejecting weed species, including seven noxious weed species that cause significant crop yield losses in Chinese farmlands (Li, 1998). However, the two WRA models incorrectly rejected 67% (2/3) of non-invasive species, which are not weeds in farmlands or ecological areas of China. This high incorrect rejection rate of non-invasive species may be due to the small data size. The Australian WRA model needs to be adjusted to increase its ability to specifically discriminate invasive species from non-invasive species that shared overlapping values. In addition, some of the questions should be simplified to increase the evaluation efficiency (Weber *et al*., 2009).

Furthermore, 18 potential invasive species from 58 Chinese plant species with WRA scores above six were selected to test their seed germination characteristics, and the invasive potentials

of these species were assessed based on their seed germination characteristics and other invasive plant functional traits. Chinese weedy species with earlier germination timings than local crop species/plant species will gain advantages in resources uptake and space occupation. In addition, Chinese weedy species will become more invasive in Canadian prairie provinces if these weedy species require less thermal times and germinate at a wider range of temperature than local crop species/plant species. In addition, other invasive plant functional traits, such as long seed longevity, prolific seed production, allelopathy or unpalatability to livestock, will make Chinese weedy species more competitive in Canadian prairie provinces. Most importantly, the potential impacts of five Chinese plant species in Canadian prairie provinces were evaluated as compared to that of their congeneric species from Canada. Based on morphological similarity within each weedy species pair, Chinese plant species may cause more negative impacts than its congeneric weedy species on Canadian prairie provinces if it has a more threatening seed germination characteristic than that of its congeneric pair; by contrast, the potential impacts of Chinese plant species may be lower than that of its congeneric weed pair from Canada if it has a less threatening seed germination characteristic.

Overall, the two WRA models in this study had high accuracy in identifying invasive species/weeds, and the second WRA model had higher efficiency. Furthermore, the invasive potentials of invasive species with WRA scores above six can be assessed via information of seed germination characteristics with other plant functional traits. Most importantly, the potential impacts of alien plant species in Canadian prairie provinces can be evaluated as compared to that of its congeneric weed species from Canadian environments with information of seed germination characteristics and other invasive plant functional traits, which provides us a new way to prevent introduction of potential invasive plant species from other areas.

6.0 APPENDIX

Appendix A. Australian Weed Risk Assessment question sheet

Answer yes (y) or no (n), or don't know (leave blank or ?), unless otherwise indicated

	Botanical name:		Outcome:	
	Common name:		Score:	
	Family name		Your name:	
	History/Biogeography			
A	**1** *Domestication/*	1.01	Is the species highly domesticated. If answer is 'no' got to question 2.01	
C	*cultivation*	1.02	Has the species become naturalised where grown	
C		1.03	Does the species have weedy races	
	2 *Climate and*	2.01	Species suited to Australian climates (0-low; 1-intermediate; 2-high)	2
	Distribution	2.02	Quality of climate match data (0-low; 1-intermediate; 2-high)	2
C		2.03	Broad climate suitability (environmental versatility)	
C		2.04	Native or naturalised in regions with extended dry periods	
		2.05	Does the species have a history of repeated introductions outside its natural range	
C	**3** *Weed*	3.01	Naturalised beyond native range	
E	*elsewhere*	3.02	Garden/amenity/disturbance weed	
A		3.03	Weed of agriculture/horticulture/forestry	
E		3.04	Environmental weed	
		3.05	Congeneric weed	
	Biology/Ecology			
A	**4** *Undesirable*	4.01	Produces spines, thorns or burrs	
C	*traits*	4.02	Allelopathic	
C		4.03	Parasitic	
A		4.04	Unpalatable to grazing animals	
C		4.05	Toxic to animals	
C		4.06	Host for recognised pests and pathogens	
C		4.07	Causes allergies or is otherwise toxic to humans	
E		4.08	Creates a fire hazard in natural ecosystems	
E		4.09	Is a shade tolerant plant at some stage of its life cycle	
E		4.10	Grows on infertile soils	
E		4.11	Climbing or smothering growth habit	
E		4.12	Forms dense thickets	
E	**5** *Plant type*	5.01	Aquatic	
C		5.02	Grass	
E		5.03	Nitrogen fixing woody plant	
C		5.04	Geophyte	
C	**6** *Reproduction*	6.01	Evidence of substantial reproductive failure in native habitat	
C		6.02	Produces viable seed	
C		6.03	Hybridises naturally	
C		6.04	Self-fertilisation	
C		6.05	Requires specialist pollinators	

C		6.06 Reproduction by vegetative propagation	
C		6.07 Minimum generative time (years)	1
A	**7** *Dispersal*	7.01 Propagules likely to be dispersed unintentionally	
C	*mechanisms*	7.02 Propagules dispersed intentionally by people	
A		7.03 Propagules likely to disperse as a produce contaminant	
C		7.04 Propagules adapted to wind dispersal	
E		7.05 Propagules buoyant	
E		7.06 Propagules bird dispersed	
C		7.07 Propagules dispersed by other animals (externally)	
C		7.08 Propagules dispersed by other animals (internally)	
C	**8** *Persistence*	8.01 Prolific seed production	
A	*attributes*	8.02 Evidence that a persistent propagule bank is formed (>1 yr)	
A		8.03 Well controlled by herbicides	
C		8.04 Tolerates or benefits from mutilation, cultivation or fire	
E		8.05 Effective natural enemies present in Australia	

A= agricultural, E = environmental, C= combined

Appendix B. One hundred and forty Canadian existing introduced plant species used for the modified WRA model

No.	Scientific name	WRA Score	Weedy status in Canada	Weed elsewhere
1	*Cichorium intybus*	19	invasive species	No
2	*Artemisia absinthium*	29	invasive species	Yes
3	*Bromus japonicus*	24	invasive species	Yes
4	*Bromus tectorum*	27	invasive species	Yes
5	*Carum carvi*	25	invasive species	Yes
6	*Cirsium palustre*	32	invasive species	Yes
7	*Digitaria ischaemum*	26	invasive species	Yes
8	*Echium vulgare*	34	invasive species	Yes
9	*Fallopia japonica*	13	invasive species	Yes
10	*Fallopia sachalinensis*	23	invasive species	Yes
11	*Galium aparine*	33	invasive species	Yes
12	*Hieracium aurantiacum*	27	invasive species	Yes
13	*Hieracium pilosella*	29	invasive species	Yes
14	*Knautia arvensis*	22	invasive species	Yes
15	*Lactuca serriola*	32	invasive species	Yes
16	*Linaria vulgaris*	36	invasive species	Yes
17	*Odontites vernus*	25	invasive species	Yes
18	*Pastinaca sativa*	33	invasive species	Yes
19	*Silene cserei*	19	invasive species	Yes
20	*Silene vulgaris*	21	invasive species	Yes
21	*Soliva sessilis*	22	invasive species	Yes
22	*Stachys palustris*	28	invasive species	Yes
23	*Carduus acanthoides*	25	invasive species	Yes
24	*Phragmites australis*	18	invasive species	Yes
25	*Coronilla varia*	21	invasive species	Yes
26	*Cardaria pubescens*	29	invasive species	Yes
27	*Sorghum halepense*	37	invasive species	Yes
28	*Lonicera japonica*	22	invasive species	Yes
29	*Apera spica venti*	15	invasive species	Yes
30	*Chondrilla juncea*	28	invasive species	Yes
31	*Taraxacum palustre*	20	invasive species	Yes
32	*Sonchus palustris*	25	invasive species	Yes
33	*Hieracium glomeratum*	25	invasive species	Yes
34	*Aira praecox*	19	invasive species	Yes
35	*Dactylis glomerata*	16	invasive species	Yes
36	*Anthoxanthum odoratum*	24	invasive species	Yes
37	*Phleum pratense*	20	invasive species	Yes
38	*Chelidonium majus*	18	invasive species	Yes
39	*Campanula rapunculoides*	24	invasive species	Yes
40	*Salsola tragus*	23	invasive species	Yes
41	*Trifolium subterraneum*	14	invasive species	Yes
42	*Melilotus officinalis*	34	invasive species	Yes
43	*Abutilon theophrasti*	21	invasive species	Yes

44	*Acroptilon repens*	30	invasive species	Yes
45	*Aegopodium podagraria*	24	invasive species	Yes
46	*Agropyron cristatum*	11	invasive species	Yes
47	*Aira caryophyllea*	24	invasive species	Yes
48	*Alliaria petiolata*	30	invasive species	Yes
49	*Amaranthus spinosus*	33	invasive species	Yes
50	*Angelica sylvestris*	30	invasive species	Yes
51	*Avena fatua*	30	invasive species	Yes
52	*Bassia scoparia*	27	invasive species	Yes
53	*Berteroa incana*	18	invasive species	Yes
54	*Bromus inermis*	24	invasive species	Yes
55	*Carduus nutans*	27	invasive species	Yes
56	*Centaurea diffusa*	33	invasive species	Yes
57	*Centaurea stoebe*	29	invasive species	Yes
58	*Chenopodium album*	22	invasive species	Yes
59	*Chenopodium murale*	24	invasive species	Yes
60	*Cirsium arvense*	33	invasive species	Yes
61	*Cirsium vulgare*	33	invasive species	Yes
62	*Conium maculatum*	30	invasive species	Yes
63	*Convolvulus arvensis*	30	invasive species	Yes
64	*Cynanchum rossicum*	32	invasive species	Yes
65	*Cynoglossum officinale*	27	invasive species	Yes
66	*Cyperus esculentus*	29	invasive species	Yes
67	*Datura stramonium*	19	invasive species	Yes
68	*Dipsacus fullonum*	33	invasive species	Yes
69	*Epipactis helleborine*	24	invasive species	Yes
70	*Eriochloa villosa*	25	invasive species	Yes
71	*Erodium cicutarium*	27	invasive species	Yes
72	*Erucastrum gallicum*	22	invasive species	Yes
73	*Euphorbia esula*	27	invasive species	Yes
74	*Galium mollugo*	27	invasive species	Yes
75	*Heracleum mantegazzianum*	29	invasive species	Yes
76	*Hesperis matronalis*	21	invasive species	Yes
77	*Humulus japonicus*	28	invasive species	Yes
78	*Hypericum perforatum*	38	invasive species	Yes
79	*Impatiens glandulifera*	31	invasive species	Yes
80	*Lamium amplexicaule*	14	invasive species	Yes
81	*Lepidium latifolium*	29	invasive species	Yes
82	*Leucanthemum vulgare*	27	invasive species	Yes
83	*Linaria dalmatica*	32	invasive species	Yes
84	*Luzula campestris*	16	invasive species	Yes
85	*Lythrum salicaria*	29	invasive species	Yes
86	*Medicago polymorpha*	27	invasive species	Yes
87	*Melilotus albus*	31	invasive species	Yes
88	*Miscanthus sinensis*	32	invasive species	Yes
89	*Mollugo verticillata*	14	invasive species	Yes

90	*Plantago lanceolata*	19	invasive species	Yes
91	*Poa annua*	28	invasive species	Yes
92	*Poa compressa*	26	invasive species	Yes
93	*Polygonum cuspidatum*	32	invasive species	Yes
94	*Ranunculus acris*	24	invasive species	Yes
95	*Raphanus raphanistrum*	31	invasive species	Yes
96	*Rorippa amphibia*	16	invasive species	Yes
97	*Rumex crispus*	28	invasive species	Yes
98	*Setaria italica*	14	invasive species	Yes
99	*Sherardia arvensis*	22	invasive species	Yes
100	*Sinapis arvensis*	23	invasive species	Yes
101	*Sonchus arvensis*	31	invasive species	Yes
102	*Sonchus oleraceus*	27	invasive species	Yes
103	*Stellaria media*	26	invasive species	Yes
104	*Thlaspi arvense*	22	invasive species	Yes
105	*Tripleurospermum perforatum*	29	invasive species	Yes
106	*Vaccaria hispanica*	15	invasive species	Yes
107	*Verbascum thapsus*	24	invasive species	Yes
108	*Veronica arvensis*	20	invasive species	Yes
109	*Vicia tetrasperma*	22	invasive species	Yes
110	*Viola arvensis*	23	invasive species	Yes
111	*Rheum palmatum*	6	non-invasive species	No
112	*Kirengeshoma palmata*	-3	non-invasive species	No
113	*Astilbe x arendsii*	-4	non-invasive species	No
114	*Iris sibirica*	10	non-invasive species	No
115	*Perovskia atriplicifolia*	-3	non-invasive species	No
116	*Thalictrum delavayi*	-3	non-invasive species	No
117	*Limonium latifolium*	-5	non-invasive species	No
118	*Linum perenne*	-4	non-invasive species	No
119	*Echinacea purpurea*	1	non-invasive species	No
120	*Catananche caerulea*	-4	non-invasive species	No
121	*Salvia nemorosa*	-3	non-invasive species	No
122	*Astrantia major*	0	non-invasive species	No
123	*Dianthus caryophyllus*	-9	non-invasive species	No
124	*Dianthus deltoides*	-2	non-invasive species	No
125	*Eryngium alpinum*	1	non-invasive species	No
126	*Galanthus nivalis*	10	non-invasive species	No
127	*Lobularia maritima*	3	non-invasive species	No
128	*Medicago sativa*	9	non-invasive species	No
129	*Origanum vulgare*	12	non-invasive species	No
130	*Penstemon barbatus*	5	non-invasive species	No
131	*Phlox paniculata*	-1	non-invasive species	No
132	*Primula denticulata*	-4	non-invasive species	No
133	*Ruta graveolens*	16	non-invasive species	No
134	*Solanum melongena*	3	non-invasive species	No
135	*Vicia lathyroides*	10	non-invasive species	No

136	*Clematis viorna*	12	non-invasive species	Yes
137	*Echinops exaltatus*	9	non-invasive species	Yes
138	*Geranium pusillum*	13	non-invasive species	Yes
139	*Molinia caerulea*	28	non-invasive species	Yes
140	*Sempervivum tectorum*	4	non-invasive species	Yes

Appendix C. List of plant species collected from Chinese farmlands

No.	Scientific names	Life form
1	*Allium chrysanthum*	Annual/forb
2	*Amaranthus retroflexus*	Annual/forb
3	*Chenopodium acuminatum*	Annual/forb
4	*Chenopodium aristatum*	Annual/forb
5	*Suaeda corniculata*	Annual/forb
6	*Atriplex patens*	Annual/forb
7	*Angelica nitida*	Perennial/forb
8	*Chamaesium paradoxum*	Biennial/forb
9	*Sphallerocarpus gracilis*	Perennial/forb
10	*Carum carvi*	Perennial/forb
11	*Cynanchum chinense*	Perennial/forb
12	*Apocynum venetum*	Perennial/forb
13	*Cynanchum amplexicaule*	Perennial/forb
14	*Cynanchum thesioides australe*	Perennial/forb
15	*Asparagus dauricus*	Perennial/forb
16	*Anaphalis spp.*	NA
17	*Saussurea salsa*	Perennial/forb
18	*Lactuca tatarica*	Biennial/perennial/forb
19	*Sonchella stenoma*	Perennial/forb
20	*Carduus crispus*	Biennial/forb
21	*Saussurea superba*	Perennial/forb
22	*Leontopodium longifolium*	Perennial/forb
23	*Cirsium esculentum*	Perennial/forb
24	*Carthamus tinctorius*	Annual/forb
25	*Saussurea pachyneura*	Perennial/forb
26	*Sonchus brachyotus*	Perennial/forb
27	*Ligularia virgaurea*	Perennial/forb
28	*Olgaea lomonosowii*	Perennial/forb
29	*Serratula centauroides*	Perennial/forb
30	*Aster tataricus*	Perennial/forb
31	*Saussurea nigrescens*	Perennial/forb
32	*Anaphalis sinica*	Perennial/forb
33	*Saussurea spp.*	NA
34	*Picris dahurica*	Perennial/forb
35	*Scorzonera albicaulis*	Perennial/forb
36	*Taraxacum asiaticum*	Perennial/forb
37	*Sonchus asper*	Annual,bennial/forb
38	*Lactuca indica*	Perennial/forb
39	*Ixeridium gracile*	Perennial/forb
40	*Xanthium sibiricum*	Annual/forb
41	*Kalimeris integrifolia*	Perennial/forb
42	*Artemisia scoparia*	Biennial/forb
43	*Artemisia sieversiana*	Annual, biennial/forb

44	*Saussurea amara*	Perennial/forb
45	*Turczaninowia fastigiata*	Perennial/forb
46	*Cephalanoplos setosum*	Perennial/forb
47	*Heteropappus altaicus*	Perennial/forb
48	*Serratula polycephala*	Perennial/forb
49	*Senecio scandens*	Perennial/forb
50	*Tripolium vulgare*	Annual, biennial/forb
51	*Artemisia lavandulaefolia*	Perennial/forb
52	*Erigeron acer*	Annual, biennial/forb
53	*Incarvillea sinensis*	Annual/perennial/forb
54	*Lappula myosotis*	Annual/biennial/forb
55	*Thlaspi arvense*	Annual/forb
56	*Lepidium apetalum*	Annual/biennial/forb
57	*Adenophora stricta*	Perennial/forb
58	*Adenophora stenanthina*	Perennial/forb
59	*Cannabis sativa*	Annual/forb
60	*Silene jenisseensis*	Perennial/forb
61	*Gypsophila oldhamiana*	Perennial/forb
62	*Salsola tragus*	Annual/forb
63	*Corispermum declinatum*	Annual/forb
64	*Suaeda glauca*	Annual/forb
65	*Atriplex centralasiatica*	Annual/forb
66	*Atriplex sibirica*	Annual/forb
67	*Corispermum chinganicum*	Annual/forb
68	*Salsola collina*	Annual/forb
69	*Calystegia hederacea*	Perennial/forb
70	*Convolvulus arvensis*	Perennial/forb
71	*Cuscuta chinensis*	Annual/forb
72	*Carex tristachya*	NA/forb
73	*Oxytropis spp.*	NA
74	*Hedysarum multijugum*	shrub
75	*Caragana korshinskii*	shrub
76	*Medicago lupulina*	Annual/biennial/forb
77	*Melilotus alba*	Annual/biennial/perennial/forb
78	*Melilotus officinalis*	Biennial/forb
79	*Vicia cracca*	Perennial/forb
80	*Glycyrrhiza uralensis*	Perennial/forb
81	*Lespedeza dahurica*	Perennial/shrub
82	*Lespedeza caraganae*	Perennial/forb
83	*Sophora flavescens*	shrub
84	*Halenia elliptica*	Annual/forb
85	*Gentiana dahurica*	Perennial/forb
86	*Gentiana macrophylla*	Perennial/forb
87	*Lomatogonium macranthum*	Annual/forb
88	*Eustoma russellianum*	Annual/biennial/perennial/forb
89	*Geranium nepalense*	Perennial/forb

90	*Erodium stephanianum*	Perennial/forb
91	*Geranium wilfordii*	Perennial/forb
92	*Amethystea caerulea*	Annual/forb
93	*Salvia spp.*	NA
94	*Stachys chinensis*	Perennial/forb
95	*Elsholtzia ciliata*	Annual/forb
96	*Scutellaria scordifolia*	Perennial/forb
97	*Galeopsis bifida*	Annual/forb
98	*Scutellaria baicalensis*	Perennial/forb
99	*Scutellaria scordifolia*	Perennial/forb
100	*Dracocephalum moldavica*	Perennial/forb
101	*Anemarrhena asphodeloides*	Perennial/forb
102	*Linum perenne*	Perennial/forb
103	*Linum usitatissimum*	Annual/forb
104	*Malva verticillata*	Annual/biennual/forb
105	*Hibiscus trionum*	Annual/forb
106	*Abutilon theophrasti*	Annual/forb
107	*Peganum multisectum*	Perennial/forb
108	*Epilobium fastigiatoramosum*	Perennial/forb
109	*Plantago maritima*	Perennial/forb
110	*Veronica eriogyne*	Perennial/forb
111	*Plantago depressa*	Annual/forb
112	*Plantago major*	Perennial/forb
113	*Plantago asiatica*	Perennial/forb
114	*Calamagrostis epigeios*	Perennial/grass
115	*Elymus dahuricus*	Perennial/grass
116	*Elymus nutans*	Perennial/grass
117	*Ptilagrostis dichotoma*	Perennial/grass
118	*Achnatherum sibiricum*	Perennial/grass
119	*Achnatherum splendens*	Perennial/grass
120	*Koeleria cristata*	Perennial/grass
121	*Deschampsia caespitosa*	Perennial/grass
122	*Trichophorum pumilum*	Perennial/grass
123	*Bromus inermis*	Perennial/grass
124	*Stipa sareptana*	Perennial/grass
125	*Poa pratensis*	Perennial/grass
126	*Avena fatua*	Annual/grass
127	*Leymus secalinus*	Perennial/grass
128	*Cenchrus echinatus*	Annual/grass
129	*Setaria viridis*	Annual/grass
130	*Pennisetum flaccidum*	Perennial/grass
131	*Panicum miliaceum*	Annual/grass
132	*Digitaria chrysoblephara*	Annual/grass
133	*Digitaria ischaemum*	Annual/grass
134	*Chloris virgata*	Annual/grass
135	*Eragrostis minor*	Annual/grass

136	*Aeluropus pungens*	Perennial/grass
137	*Cleistogenes chinensis*	Perennial/grass
138	*Elymus sibiricus*	Perennial/grass
139	*Echinochloa crusgalli*	Annual/grass
140	*Polygonum macrophyllum*	Perennial/forb
141	*Polygonum convolvulus*	Annual/forb
142	*Fagopyrum tataricum*	Annual/forb
143	*Polygonum viviparum*	Perennial/forb
144	*Polygonum divaricatum*	Perennial/forb
145	*Polygonum sibiricum*	Perennial/forb
146	*Rumex patientia*	Perennial/forb
147	*Delphinium grandiflorum*	Annual/forb
148	*Delphinium kamaonense*	Perennial/forb
149	*Thalictrum petaloideum*	Perennial/forb
150	*Anemone rivularis*	Perennial/forb
151	*Thalictrum simplex*	Perennial/forb
152	*Aconitum gymnandrum*	Annual/forb
153	*Sanguisorba officinalis*	Perennial/forb
154	*Potentilla chinensis*	Perennial/forb
155	*Potentilla spp.*	NA
156	*Potentilla chinensis*	Perennial/forb
157	*Asperugo procumbens*	Annual/forb
158	*Rubia cordifolia*	Perennial/forb
159	*Parnassia palustris*	Perennial/forb
160	*Parnassia trinervis*	Perennial/forb
161	*Saxifraga stolonifera*	Perennial/forb
162	*Euphrasia regelii*	Annual/forb
163	*Euphrasia pectinata*	Annual/forb
164	*Pedicularis chinensis*	Annual/forb
165	*Lycium ruthenicum*	Shrub
166	*Hyoscyamus niger*	Biennial/forb
167	*Solanum nigrum*	Annual/perennial/forb
168	*Datura stramonium*	Annual/forb
169	*Tribulus terrester*	Annual/perennial/forb

Appendix D. Weed risk assessment scores for 58 Chinese plant species

No.	Scientific names	WRA scores	Weedy status in China
1	*Xanthium sibiricum*	33	Weed
2	*Rubia cordifolia*	27	Weed
3	*Polygonum convolvulus*	26	Weed
4	*Chenopodium acuminatum*	25	Weed
5	*Calystegia hederacea*	25	Weed
6	*Digitaria chrysoblephara*	23	Weed
7	*Erodium stephanianum*	15	Weed
8	*Chenopodium aristatum*	11	Weed
9	*Chloris virgata*	30	Weed
10	*Rumex patientia*	28	Weed
11	*Senecio scandens*	27	Weed
12	*Elymus sibiricus*	27	Weed
13	*Amethystea caerulea*	26	Weed
14	*Artemisia sieversiana*	24	Weed
15	*Serratula centauroides*	24	Weed
16	*Artemisia lavandulaefolia*	23	Weed
17	*Sphallerocarpus gracilis*	22	Weed
18	*Atriplex patens*	22	Weed
19	*Plantago depressa*	22	Weed
20	*Lepidium apetalum*	22	Weed
21	*Plantago asiatica*	20	Weed
22	*Bromus inermis*	18	Weed
23	*Cirsium esculentum*	18	Weed
24	*Dracocephalum moldavica*	17	Weed
25	*Kalimeris integrifolia*	16	Weed
26	*Aconitum gymnandrum*	16	Weed
27	*Saxifraga stolonifera*	15	Weed
28	*Sanguisorba tenuifolia*	14	Weed
29	*Cynanchum chinense*	13	Weed
30	*Heteropappus altaicus*	12	Weed
31	*Tripolium vulgare*	12	Weed
32	*Turczaninowia fastigiata*	12	Weed
33	*Corispermum chinganicum*	12	Weed
34	*Aster tataricus*	12	Weed
35	*Elsholtzia densa*	12	Weed
36	*Sophora flavescens*	11	Weed
37	*Pennisetum flaccidum*	11	Weed
38	*Adenophora stricta*	10	Weed
39	*Incarvillea sinensis*	10	Weed
40	*Delphinium kamaonense*	10	Weed
41	*Elymus dahuricus*	10	Weed
42	*Atriplex centralasiatica*	10	Weed
43	*Potentilla chinensis*	10	Weed
44	*Scutellaria scordifolia*	9	Weed

45	*Glycyrrhiza uralensis*	9	Weed
46	*Potentilla chinensis*	9	Weed
47	*Lespedeza dahurica*	8	Weed
48	*Asparagus dauricus*	7	Weed
49	*Suaeda glauca*	6	Weed
50	*Saussurea amara*	17	Weed
51	*Picris japónica*	15	Weed
52	*Aeluropus pungens*	13	Weed
53	*Koeleria cristata*	11	Weed
54	*Thalictrum Simplex*	9	Weed
55	*Thalictrum petaloideum*	9	Weed
56	*Anemone rivularis*	14	Non-weed
57	*Silene jenisseensis*	10	Non-weed
58	*Dianthus chinensis*	6	Non-weed

Appendix E. List of worst weeds in China

Scientific name	Family	Life history
Alternanthera philoxeroides	Amaranthaceae	Perennial
Malachium aquaticum	Caryophyllaceae	Perennial/Annual
Chenopodium album	Chenopodiaceae	Annual
Cephalanoplos segetum	Compositae	Perennial
Eclipia prostrata	Compositae	Annual
Hemistepta lyrata	Compositae	Annual/Biennial
Calystegia hederacea	Convolvulaceae	Perennial
Capsella bursa pastoris	Cruciferae	Biennial
Descurainia Sophia	Cruciferae	Annual/Biennial
Acalypha australis	Euphorbiaceae	Annual
Vicia sativa	Leguminosae	Biennial
Rotala indica	Lythraceae	Annual
Polygonum aviculare	Polygonaceae	Annual
Polygonum lapathifolium	Polygonaceae	Annual/Biennial
Porrtulace oleracea	Portulacaceae	Annual
Galium aparine	Rubiaceae	Annual/Biennial
Sagittaria pygmaea	Alismataceae	Annual
Cyperus difformis	Cyperaceae	Annual
Cyperus iria	Cyperaceae	Annual
Cyperus rotundus	Cyperaceae	Perennial
Eleocharis yokoscensis	Cyperaceae	Perennial
Juncellus serotinus	Cyperaceae	Perennial
Scirpus planiculmis	Cyperaceae	Perennial
Alopecurus aequalis	Gramineae	Annual/Biennial
Avena fatua	Gramineae	Perennial
Beckmannia syzigachne	Gramineae	Perennial
Digitaria ciliaris	Gramineae	Annual
Digitaria sanguinalis	Gramineae	Annual
Echinochloa crusgalli	Gramineae	Annual
Echinochloa crusgalli var. mitis	Gramineae	Annual
Echinochloa hispidula	Gramineae	Annual
Eleusine indica	Gramineae	Annual
Imperata cylindrical	Gramineae	Perennial
Leptochloa chinensis	Gramineae	Annual
Setaria viridis	Gramineae	Annual
Monochoria vaginalis	Pontederiaceae	Annual
Potamogeton distinctus	Potamogetonaceae	Annual

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