EXOTIC INVASIVE PLANTS IN KENTUCKY

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2010

Recommended Citation

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ABSTRACT OF THESIS

EXOTIC INVASIVE PLANTS IN KENTUCKY

Invasion of exotic species is a significant problem in natural ecosystems, reaching epidemic proportions and resulting in significant economic losses. However, insufficient knowledge of explicit spatial distribution of invasive species hinders our ability to prevent and/or mitigate future invasion. In this study, we demonstrate the use of existing voluntary data to survey invasive plant species in Kentucky. We also reconstructed the historical distribution of 16 exotic invasive plants typical to Kentucky using herbarium records. We found that Kentucky is facing a large threat from exotic invasive plants as they are reported throughout most counties. The distribution maps for four of the top 10 most reported invasive species revealed that Kentucky is presently or was previously a front of invasion. The majority of the 16 targeted invasive species were scattered throughout Kentucky with no concentrations within particular regions. Cumulative curves of occupied counties over time fit a “J” shape expansion curve, which indicates the potential for further future invasion. This study demonstrates the usefulness of voluntary data and herbarium data to reconstruct the historical and current distribution of invasive species. Further studies on other invasive species can take advantage of information associated with herbarium specimens to achieve more fruitful results.

KEYWORDS: Exotic invasive plant, historical distribution, herbarium records, expansion rate, predominant land use type.

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June 18, 2010
EXOTIC INVASIVE PLANTS IN KENTUCKY

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EXOTIC INVASIVE PLANTS IN KENTUCKY

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Agriculture at the University of Kentucky

By
Yu Liang
Lexington, Kentucky
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Lexington, Kentucky
2010

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ACKNOWLEDGEMENTS

The following thesis benefited from the help of many people. I wish to express sincere appreciation to my advisor, Dr. Songlin Fei, who recruited me from China and changed my life for the better. I thank him for his understanding and support throughout my Master’s research. Thanks also go to my committee members: Dr. Jonathan D. Green, Mr. Robert Paratley, and Dr. John Lhotka. I thank Dr. Green for providing the weed identification data that served as the foundation of my research. His advising and support was also very important for my thesis. Rob, I appreciate your help and your kind advice every time I burst into your office or intercepted you on your way home. Dr. Lhotka, you made my graduation possible and always gave me strength and courage to face the difficulties I encountered.

Thanks to all the herbarium curators who welcomed me, sent me data, or allowed me to download data from their databases. Your persistence and hard work is critical for advancing science. Many thanks go to my colleagues: John Hast, Ben Augustine, Kevin Devine, David Parrott, and Dr. Liang Liang for their encouragement and peer reviews.

My deepest thank goes to my family, whose support have helped me during the days I study abroad. Last but not least, my deepest love goes to my fiancée Shan Liu for her love, support, sacrifice, and understanding during the whole period.

This thesis is based upon work supported by the Cooperative State Research, Education and Extension Service, U.S. Department of Agriculture, under Agreement No. 2008-34628-19532. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture.
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CHAPTER ONE: Introduction

THE THREAT OF EXOTIC INVASIVE SPECIES

Exotic species are those that have been introduced outside their native ranges purposely or accidentally (Williams and Grosholz 2008). Not all exotic species become invasive after they were introduced. Some exotic species, such as rice, corn, and other food crops, now provide more than 98% of food in the U.S. worth approximately $800 billion per year (Pimentel et al. 2005). Some exotic species, however, cause a decrease in native species diversity, and alter the function of ecosystems (Reid et al. 2009; Ward and Jasieniuk 2009; White et al. 2008). In this thesis, an invasive species is defined as an exotic species whose introduction does or is likely to cause economic or environmental harm, or harm to human health (Rossman 2001).

Although species establish and spread on their own, increased mobility of humans have brought about an unparalleled movements of exotic species (Botham et al. 2009; Chauvel et al. 2006; Flory and Clay 2009; Reichard and White 2001; Rejmanek 1996). Approximately 50,000 non-native species have been introduced into the United States alone (Pimentel et al. 2005), compared with a total of about 17,000 native species (Morse 1995). These invasive alien species are considered a threat to native species, and are widely considered responsible for the decline of species diversity and ecosystem stability. Exotic invasive species eliminate native species by utilizing various mechanisms, such as resource competition (Fasola et al. 2009; McNatty et al. 2009; Snyder et al. 2009; Strubbe and Matthysen 2009) and predation (Bellingham et al. 2010; Kwong et al. 2009; Pichlova-Ptcnikova and Vanderploeg 2009; Piggott et al. 2008; Strecker and Arnott
They crowd out native species from gene pool, which reduces the diversity of species (Adams and Engelhardt 2009; Anderson and Rosemond 2007; Davis 2003). The loss of biodiversity, along with the effect of climate change, may decrease the persistence of ecosystems to stochastic events such as natural disasters and insect pests (Bradley 2010; Callaway and Maron 2006; Manchester and Bullock 2000). Another concern about invasive exotic species relates to increasing economic loss in agriculture, forestry and other segments of the U.S. economy. In agriculture, invasive plants crowd out food crops for sunlight and water resources (Allaie et al. 2006), reduce crop and forage quality (Stewart et al. 2009; Suckling and Brockerhoff 2010), and in some case poison livestock species (Legere 2009). The financial impacts and management costs due to loss of productivity, costs of herbicides, and other control measures for invasive species is estimated to exceed $120 billion annually (Pimentel et al. 2005). Invasive disease may also directly affect human health (Molocznik 2004; Tuiten et al. 2009). For example, West Nile virus arrived in the United States as recently as 1999 (Edman 2004). In 2003, 4200 people were infected, resulting in 284 deaths (Wonham et al. 2004).

EXOTIC INVASIVE PLANTS IN KENTUCKY

Kentucky faces a huge challenge from exotic species invasion, making this a problem pressing for a solution. Invasive species can invade into Kentucky from seven surrounding states. Also, Kentucky is located around 40 degree north latitude, where is the species transition zone for cool season plants and warm season plants. Longitudinally, KY has many ecoregions, such as mountains in the east, plain in the central, and wetland in the west. Its unique geographic location increases the diversity of
invasive species in Kentucky. Additionally, the moderate, relatively humid climate in Kentucky is similar with that in Europe and eastern Asia where most of North American invasive species came from. It has been reported that, among all the vascular plants, a quarter of them were introduced (Jones 2005). Ninety-two plant species have been declared as exotic invasive species by Kentucky Exotic Pest Plant Council (KY-EPPC 2008). The following are the major exotic invasive plants included in this study. General introductions and biological traits of these invasive plants are described below.

**Amur honeysuckle**

Amur honeysuckle (*Lonicera maackii* (Rupr.) Herder) is a deciduous shrub native to eastern Asia (Luken and Thieret 1996). It was introduced into North America in 1896 as an ornamental shrub (Luken and Mattimiro 1991). Amur honeysuckle occurs throughout the eastern United States (Goodell et al. 2010). With the seeds being dispersed by birds and mammals (Bartuszevige and Gorcho 2006; Luken and Goessling 1995), this plant forms a dense understory which restricts native plant growth in forests, and can adversely affect populations of native species in disturbed open areas and forest edge (Castellano and Boyce 2007; Hartman and McCarthy 2008; Miller and Gorcho 2004; Swab et al. 2008). Because of its floral and fruit display, the species is still widely available in nurseries and botanical gardens across the country (Luken and Thieret 1996). The distribution pattern of Amur honeysuckle has been studied in southwestern Ohio (Medley 1997). The study found honeysuckle abundances were highest in the forest edge area and small discontinuous patches. Colonization in understory of forest and subsequent development for Amur honeysuckle was also studied using sample populations in Ohio (Deering and Vankat 1999). Scattered distributions in multiple locations likely contribute to the colonization of this invasive shrub. Restoration of natural understory ecosystem was also
successfully carried out after the removal of this invasive shrub using two different herbicides (Hartman and McCarthy 2004).

**Annual bluegrass**

Annual bluegrass (*Poa annua* L.) is a cool-season annual, biennial, or perennial grass. It is a native to Europe and now wildly distributed around the world. It thrives in lawns, gardens, pastures, roadsides, and disturbed areas throughout the U.S. (USDA 2010). Annual bluegrass can reduce nutrient availability in the upper soil horizons by forming dense mats (Johnson 1979). The seeds of this weed can be spread by birds (Koshy 1969). Vegetative portions are probably eaten by large mammals which also contributes the spread of this weed. A wide range of invertebrates also feed on annual bluegrass (Beard et al. 1978).

**Autumn olive**

Autumn olive (*Elaeagnus umbellata* Thunb.) was introduced into the United States in 1830 from eastern Asia as an ornamental plant (Catling et al. 1997). This shrub species is found in the east and northwestern United States (Goldstein et al. 2009). Unlike many other introduced species which prefer colonizing in forest edge areas (Tlig-Zouari et al. 2009), autumn olive also succeeds in the adjacent interiors of forest (Yates et al. 2004). It often crowds out native plant species by creating dense thickets and interfering with natural plant succession and nutrient cycling with *Frankia*, a nitrogen-fixing endosymbiont (Brantley and Young 2010; Goldstein et al. 2009; Yates et al. 2004). Autumn olive produces a great amount of small fleshy drupes, which are consumed by birds or mammals, and may rapidly expand over large distances (Ahmad et al. 2006; Knapp et al. 2008; McCay et al. 2009).
Barnyardgrass

Barnyardgrass (Echinochloa crus-galli (L.) Beauv.) is an annual of Eurasian origin that occurs throughout the continental United States (Kaufman and Kaufman 2007). Barnyardgrass invades cultivated fields, waste places, floodplains and other disturbed area (Brod 1968). Although it is invasive, it is not strongly competitive with native plants except in low, moist, disturbed areas (Maun 1977). Barnyardgrass is tolerant to long wet periods and withstands considerable salt and alkali (Assemat et al. 1981). It is self-pollinating and a prolific seed producer that can produce as many as one million seeds. The seed viability drops after one year, but can last up to 13 years (Kennedy et al. 1980).

Canada thistle

Canada thistle (Cirsium arvense (L.) Scop.), a cool season perennial, is native to Europe and probably arrived in North America in the early 1600s (Kaufman and Kaufman 2007). It grows in the northern United States and southern Canada (USDA 2010). Canada thistle is particularly problematic in farms and pastures because it causes economic loss by reducing crop yields and pasture productivity (Demers et al. 2005; Reece and Wilson 1983; Zimdahl and Foster 1993). This species produces large quantities of “bristly-plumed” seeds which are dispersed by wind or water (Hayden 1934). Its seeds can remain viable for over 20 years in the soil (Lalonde and Roitberg 1994). Canada thistle can also regenerate vegetatively by roots or shoot sprouts (Laubhan and Shaffer 2006). Its invasiveness was soon recognized after it was introduced into the U.S.. Since then, a lot of research work has been carried out about the control strategy for this weed (Foote et al. 1970; Peschken and Wilkinson 1981; Wedekind 1991). Spatial
distribution of this weed has been studied in Germany and a spatially explicit simulation model for the dispersal of Canada thistle was created to predict further invasion of this weed (Belde and Mayer 2002).

**Climbing euonymus**

Climbing euonymus (*Euonymus fortunei* (Turcz.) Hand.-Maz.) is native to eastern Asia and was introduced in 1907 from China (Kaufman and Kaufman 2007). This evergreen vine grows in the eastern United States, from New York to Mississippi (USDA 2010). Climbing euonymus is an ever-green clinging vine widely used in residential landscaping (Harris et al. 2009). It outcompetes the natural vegetation by forming dense thickets which restricts native species growth (Swearingen 2009). Its vines can climb overtop native plants and block sunlight (Kaufman and Kaufman 2007). Climbing euonymus is sold in commercial nurseries and spreads by horticultural trade (Boyer et al. 2008). It escapes the gardens through seed dispersal by birds and small mammals, and then invades into neighborhoods vegetatively (Rehder 1993).

**Common chickweed**

Common chickweed (*Stellaria media* (L.) Vill.), an annual weed introduced from Eurasia, was first recorded in New England in 1672 (Turkington et al. 1980). It was probably brought as an herbal remedy by European explorers and emigrants (Shotwell 1993). Common chickweed is now found throughout the United States (USDA 2010). Its seed was probably spread by emigrants who cultivated the plant for medicinal and leafy vegetable use and by seeds contaminating grain shipments (Miura and Kusanagi 2001).
The weed is particularly well adapted to disturbed agricultural habitats by its ability to germinate throughout the year in temperate climates, the short after-ripening of the seed, and a short growth period from germination to flowering and seed set (Inderjit and Dakshini 1998). Common chickweed seeds can remain viable in the soil for at least 30 years (Storkey and Cussans 2000).

**Common lespedeza**

Common lespedeza (*Kummerowia striata* (Thunb.) Schindl.), a Japanese annual herb, was first reported growing in Georgia in 1846 (Kaufman and Kaufman 2007). Common lespedeza is widely planted and naturalized in the southeastern U.S. (USDA 2010). This plant is used extensively on crop lands and pastures for hay, grazing and soil improvement. Common lespedeza occurs in roadsides, open area, and other disturbed sites. It may become invasive in some regions or habitats and may displace desirable vegetation if not properly managed (Nakatsubo 1995). This weed has a rapid ability to spread through seed production and the seedlings have high vigor (Nakatsubo 1995).

**Common reed**

Common reed is a large, perennial grass that grows to over 15 feet in height. Both native and introduced forms of (*Phragmites australis* (Cav.) Trin. ex Steud.) exist in the United States (Catling and Carbyn 2006; Meadows and Saltonstall 2007). The introduced (European) genotype of common reed is held to be responsible for the widespread invasion of this plant (T’ulbure et al. 2007). Introduced common reed occurs within all of the lower 48 states (USDA 2010). Their dense stands outcompete native aquatic or marsh
plants and eventually reduce flora diversity (Able et al. 2003; Minchinton 2006). This species was reported to reproduce either by seed or by rhizomes (Brisson et al. 2008). Historical spread and dispersal pathways of this weed have been analyzed using herbarium records in Quebec, Canada (Lelong et al. 2007). The study suggested that the development of the highway network in the 1960s and 1970s strongly contributed to the inland expansion of the exotic genotype.

**Ground ivy**

Ground ivy (*Glechoma hederacea* L.), a perennial herb, was introduced as an ornamental or medicinal plant from Eurasia as early as the 1800s (Kaufman and Kaufman 2007). This invasive weed is common throughout the U.S. except in the Southwest. Trailing over the ground, ground ivy forms a thick ground cover that prevents the establishment and growth of other native plants (Fernande 1971). It is problematic in lawn and also can be found in natural area. Ground ivy prefers the moist ground, shade of floodplains and disturbed area (Kohler et al. 2004a). Stems root at the nodes and stem fragments are the major source of spread (Mitich 1994).

**Japanese honeysuckle**

A perennial vine species from eastern Asian, Japanese honeysuckle (*Lonicera japonica* Thunb.) was introduced into the U.S. as a horticultural plant by a gardener in 1806 (Schierenbeck 2004). It currently occurs across the southern United States and New England (USDA 2010). Japanese honeysuckle grows best in high-light forest edges and open fields (Robertson et al. 1994). It forms a dense ground cover in the understory,
outcompeting native plants (Belote and Weltzin 2006; Merriam 2003). Japanese honeysuckle is still widely available in the nurseries and spreads through the horticultural trade as an ornamental plant (Kowarik 2003). Further invasion of this species is facilitated via birds, mammals, and vegetative spread (Schierenbeck 2004). In Oklahoma, the historical spread of Japanese honeysuckle over the past 100 years has been reconstructed using herbarium data (Crawford and Hoagland 2009). Maps of the collection records of this invasive vine illustrated no discernible spatial invasion or expansion pattern.

Japanese knotweed

Japanese knotweed (*Polygonum cuspidatum* Sieb. & Zucc.), a herbaceous perennial plant, was introduced from Japan to the United States in the late 1800s (Kaufman and Kaufman 2007). This species occurs across 40 states in the U.S., from Maine to Louisiana and in several midwest and western states (USDA 2010). Japanese knotweed reproduces primarily by vegetative means via rhizomes, yet prolific seed reproduction is also observed (Zika and Jacobson 2003). Japanese knotweed spreads quickly, forming dense stands that exclude indigenous species (Weston et al. 2005). Its underground root system and viable seed make it extremely difficult to eradicate (Forman and Kesseli 2003). The historical spread of this weed have been recreated using Index Herbarium data in 2003-2004 in North America (Barney 2006). The study indicated that Japanese knotweed frequently distributed along waterway and road suggesting large-scale human related spread across North America. Another study in Canada using Invasive Alien Plant Program data suggested over half of the suitable habitat for Japanese knotweed in British
Columbia have already been occupied, indicating there are still significant areas to be invaded (Bourchier and Van Hezewijk 2010).

**Japanese stiltgrass**

Japanese stiltgrass (*Microstegium vimineum* (Trin.) A. Camus), an annual herbaceous plant, was first introduced into the United States in Tennessee around 1919 (Fairbrot.De and Gray 1972a). Japanese stiltgrass is primarily established in 25 states, from Maine to Florida, west to Texas (USDA 2010). This species spreads mainly by wind or water due to its extremely light seeds (Cheplick 2005; Mehrhoff 2000). Dense patches of Japanese stiltgrass established after habitat disturbance can outcompete native communities by robbing them of sunlight (Rauschert et al. 2010). It also alters soil structures and properties, such as pH, further interfering with native plants regeneration (Ehrenfeld et al. 2001; Hunt and Zaremba 1992; Kourtev et al. 1998). The spread and distribution of this weed have been reported along the Hudson River in New York and reported from three sites in Connecticut (Hunt and Zaremba 1992). A landscape-level survey of Japanese stiltgrass at east Tennessee was conducted. The study suggested different factors may interact to control the distribution and performance of this species locally (Cole and Weltzin 2004).

**Kudzu**

Kudzu (*Pueraria montana* var. *lobata* (Willd.) Maesen & S.M. Almeida) was a perennial vine introduced into the United States from Japan in 1876 at the Philadelphia Centennial Exposition (Miller 1983). It has been widely used for soil erosion control
during the 1930s (Forseth and Innis 2004). Kudzu is common throughout most of the southeastern United States and recently has also been discovered in northern states (Forseth and Innis 2004; Lamont and Young 2002). This invasive vine thrives in forest edge areas, abandoned fields, and disturbed areas, where sunlight is abundant (Newton et al. 2008). Kudzu’s vigorous growth kills trees by girdling, while its dense of leaves smother native plants (Forseth and Innis 2004). This plant spreads vegetatively in most cases (Merriam 2003). Rapid stem elongation and frequent rooting at nodes makes this invasive vine effective in its domination of disturbed areas and habitat gaps (Forseth and Innis 2004; Merriam 2003). A series of control methods have been developed to control this invasive vine, such as herbicide (Dickens and Buchanan 1971) and biocontrol using soybean rust (*Phakopsora pachyrhizi*) (Hershman et al. 2006; Zidack and Backman 1996). A systematic survey for kudzu biocontrol agents in China was also underway and several of kudzu foliage, seed, stems, and roots associated insects have been reported (Sun et al. 2006).

**Multiflora rose**

Multiflora rose (*Rosa multiflora* Thunb. ex Murr.) was imported into the eastern United States in 1866 from eastern Asia as an ornamental and farm hedge (Steavenson 1946). It occurs throughout most of the United States except in the Rocky Mountains and deserts (USDA 2010). It tolerates a wide range of soil, moisture, and light conditions, which allows it to grow aggressively into riparian areas, thickets, and woodlands (Merriam 2003). In herbaceous communities, impenetrable thickets of multiflora rose exclude native shrubs and herbs from establishing (Yurkonis et al. 2005). Multiflora rose
increases native species seed removal and affects forest regeneration by providing cover for small seed predators (Meiners and LoGiudice 2003). It is a prolific producer and its seeds can remain viable in the soil for up to 20 years (Banasiak and Meiners 2009). Birds are a primary dispersal method for the multiflora rose (Borgmann and Rodewald 2004). However, this invasive shrub can also reproduce vegetatively (Szafoni 1991). Control methods of multiflora rose have been accessed in many ways (Derr 1989; Hindal and Wong 1988). For example, rose rosette disease had been used for biocontrol of this invasive shrub (Epstein et al. 1997).

Musk thistle

Musk thistle (Carduus nutans L.), a biennial weed, was first recorded in central Pennsylvania in 1852 from its native range of Europe and western Asia (Kaufman and Kaufman 2007). This species occurs throughout the United States except for Florida (USDA 2010). Musk thistle forms dense stands, reducing yield in pastures considerably by crowding out forage plants (Moore et al. 1989; Popay et al. 1989; Wardle et al. 1995). Musk thistle reproduces and spreads only by seed. One single plant can produce thousands of seeds which are easily dispersed by wind or water (Jongejans et al. 2008). Its seeds may remain viable for up to ten years, making it difficult to eradicate (Jongejans et al. 2006; Metcalf et al. 2009). Effective methods available for control of musk thistle have also been developed in several countries beside the U.S. such as New Zealand and Australia (Moore et al. 1989; Shea et al. 2006).
**Poison-hemlock**

Poison-hemlock (*Conium maculatum* L.), a European biennial weed, was first noticed in the United States in the 1800s (Kaufman and Kaufman 2007). It grows throughout southern Canada and the United States (USDA 2010). Poison-hemlock can grow quickly to occupy disturbed areas and displace native vegetations in moist areas (Schmida 1974). This weed produces coniine, an alkaloid which is poisonous to both livestock and humans (Bowman and Sanghvi 1963; Fairbairn and Challen 1959; Lopez et al. 1999). Poison-hemlock reproduces only from seeds which can adhere to farm equipments, clothes, and mud (Goeden and Ricker 1982). Its seeds can also be carried by water and wind (Knight 1987).

**Princesstree**

Princesstree (*Paulownia tomentosa* [Thunb.] Sieb. & Zucc. ex Steud.) was imported to Europe by the Dutch East India Company in the 1830s as an ornamental and brought to North America soon after (Langdon and Johnson 1994). Princesstree occurs in eastern U.S., from Maine to Texas (USDA 2010). By tolerating drought conditions and acidic soils, it is able to adapt to a wide variety of habitats (Moore and Lacey 2009). One single princesstree can produce millions of seeds, which are easily dispersed by wind or water (Grubisic et al. 1985). These seed can germinate rapidly in many soil types (Hyatt and Casper 2000; Moore and Lacey 2009). This invasive tree can also reproduce from its extensive root system (Mueller et al. 2001). Princesstrees was reported to displace native plant species in disturbed areas, burns, and forest edges (Ede et al. 1997; Essl 2007).
**Sericea lespedeza**

Sericea lespedeza (*Lespedeza cuneata* (Dumont) G. Don), a perennial legume native to eastern Asia, was introduced in Virginia in 1899 as a forage species (Kaufman and Kaufman 2007). It occurs throughout the eastern United States from New York to Texas (USDA 2010). Once established, this species displaces native plants and hinders their habitat by spreading dynamically (Allred et al. 2010). This plant is a prolific producer as it can produce as much as 670 kg of seed/hectare annually which remain viable for over 30 years (Logan et al. 1969). Recently, hyperspectral imagery has been used to detect the sericea lespedeza in pastureland in mid-Missouri and the quantitative distribution of sericea volume was then mapped using an empirical regression model (Wang et al. 2008).

**Start-of-Bethlehem**

Start-of-Bethlehem (*Ornithogalum umbellatum* L.) is a European herbaceous plant that grows from bulbs with annual renewal (Demars 1994). It was most likely introduced into the U.S. as a horticultural plant. The exact date of introduction is not known, but there were reports of large stands of it in 1940 in the forests of Indiana (Demars 1994). Currently, this plant is found throughout the states except New Mexico, Nevada, Arizona, Colorado, Wyoming, Montana, and North Dakota (USDA 2010). It was most likely dispersed via additional plantings as well as the bulbs being washed downstream (Moret et al. 1991). Star-of-Bethlehem causes potential threats to native vegetation by competing for the nutrient (Gadella 1972). Star-of-Bethlehem is non-responsive to several herbicides. Research studies found that paraquat provided 70 to 78% control (Main et al. 2004).
**Tree-of-heaven**

Tree-of-heaven (*Ailanthus altissima* (P. Mill.) Swingle) is a small to medium-sized deciduous tree native to China (Ding et al. 2006). It was introduced from China into Europe in 1751 and then introduced via Europe to North America in 1784 (Swingle 1916). It is now widely distributed across the United States, occurring in 42 states, from Maine to Florida and west to California (USDA 2010). Once established, tree-of-heaven sends out many root sprouts, rapidly forming dense thickets that prevent native species growth (Call and Nilsen 2005). Its root system can cause damage to roadways, sidewalks, and sewer structures. This tree species is also a prolific seed producer; a mature tree-of-heaven can produce up to 350,000 seeds a year (Kaproth and McGraw 2008). Seeds maintain a high germination rate even after 5 months (Kaproth and McGraw 2008). This invasive species is able to disperse long distances into fields and fragmented landscapes by wind or water (Kaproth and McGraw 2008; Kowarik and Saumel 2008; Landenberger et al. 2007). In addition to its prolific reproduction and extensive root system, tree-of-heaven also has allelopathic effects on other tree species growing in its neighborhood by producing phytotoxic compounds from roots and leaves (Ding et al. 2006; Heisey 1990).

Recently, studies about the invasion mechanism and control method of tree-of-heaven have been conducted. Call (2005) suggested the positive association between tree-of-heaven and native black locust (*Robinia pseudoacacia*) along the highly disturbed skid trails. Ding (2006) reviewed literature about enemies of the plant in order to access the potential biological control of this plant. However, the dispersal pattern of tree-of-heaven was only reported in southwest Ohio, where tree-of-heaven frequently dominate on the edge of forest instead of the interior (Espenschied-Reilly and Runkle 2008).
White mulberry

White mulberry (*Morus alba* L.), a deciduous tree native of eastern Asia, was most likely introduced to the United States as an ornamental tree in the mid-1800s (Kaufman and Kaufman 2007). It grows across the country except for Nevada (USDA 2010). During colonial times, white mulberry was widely planted to establish a silk industry in the United States (Noe 2009). Its seeds are spread by birds and mammals that feed on the fruits. It can also reproduce vegetatively from its roots (Ghersa et al. 2002). White mulberry forms dense thickets that exclude other native plant species (Burgess and Husband 2006). The hybridization of white mulberry and native red mulberry (*Morus rubra* L.) resulted in threats to the survival of red mulberry by displacing this native species (Burgess and Husband 2006).

Overall, invasive plants appear to have specific traits or combinations of specific traits that allow them to outcompete native species. The common traits of these sixteen invasive plants include: fast growth, tolerance of a wide range of environmental conditions, the ability to reproduce both asexually as well as sexually, high dispersal ability, and association with human activities (Rejmanek and Richardson 1996).

DISTRIBUTION OF INVASIVE PLANTS

To stop or mitigate the invasion of existing and new emerging species, effective Early Detection and Rapid Response (EDRR) systems are needed to detect the occurrence of invasions (Chornesky et al. 2005; Wittenberg and Cock 2001). These EDRR systems include functions for identifying the potential high priority species lists, providing
adequate and timely information of species distribution patterns to decision-makers and the public, and determining the at-risk sites by utilizing predictive models (Chornesky et al. 2005). In EDRR systems, identifying explicit spatial distribution pattern of exotic invasive species in regions outside their native range is a fundamental component (Hulme 2006). The spatial distribution pattern of alien plants may either predict the species distribution for a site, or further our understanding of factors that influence these distributions (Higgins et al. 1999). This information is essential for planning eradication, containment, and control strategies and treatments. Unfortunately, a common defect of most EDRR systems is that they have insufficient power to detect the significant change in the distribution of invasive species due to its limited sampling sites (Van Strien et al. 1997). However, sampling more sites to increase the power of surveys is impractical because of the enormous amounts of manpower and material resources needed. The initiatives of citizen volunteers may provide a less costly approach and strengthen the ability of accurate predicting the invasion trend (Engler et al. 2004). Several regional systems, Early Detection and Distribution Mapping System (EDDMapS, http://www.eddmaps.org) created by Southeast Exotic Pest Plant Council (SE-EPPC), Invasive Plant Atlas of New England (IPANE, http://www.ipane.org) and Invasive Plant Atlas of MidSouth (IPAMS, http://www.gri.msstate.edu/ipams/), have taken advantage of such citizen scientist efforts. The development and utilization of voluntary data systems can add a new catalyst for understanding natural phenomenon, yet its application in natural resource systems is limited (Orr et al. 2007).

Recognizing the need to identify an invasion of exotic species, many researchers have begun to reconstruct the historical distribution of invasive species. Recently, progress in
this respect has been made by consulting real or virtual herbarium collections (Crawford and Hoagland 2009; Delisle et al. 2003; Lavoie et al. 2007; Miller et al. 2009; Stadler et al. 1998). For example, Chauvel (2006), using herbarium specimens in France and in bordering countries, identified how annual ragweed (*Ambrosia artemisiaefolia* L.) initially arrived in France and subsequently spread out over time. However, we must be cautious when the reconstruction of historical spread of invasive species is based on herbarium specimens. Few studies have taken into consideration the biased nature of natural history collections such as: unequal sampling effort over time, non-random geographical representation, and disproportionately represented taxa (Delisle et al. 2003). For instance, the increase in the number of specimens of an invasive species may indicate an increase in abundance, or simply may mean an increase in the overall collecting effort that year or decade (Crawford and Hoagland 2009). To remove such biases, Delisle et al. (2003) developed a method by selecting indigenous species to provide a collection trend in the study region. By comparing the collection trend, the increasing collections of invasive species suggests the increase of the invasive species in range or abundance. Although the data from herbarium specimens suffer from several biases, they constitute a valuable source of information to document the early stages of the invasion process (Chauvel et al. 2006; Lelong et al. 2007; Stadler et al. 1998; Weber 1998; Wu et al. 2005). Plant specimens stored in herbaria are usually well preserved, so the identification of species can be validated or corrected (Lelong et al. 2007). Furthermore, each specimen includes a label, usually with information about sampling location and date, which makes the reconstructing of historical spread feasible (Delisle et al. 2003; Ponder et al. 2001).

Little knowledge is available about the spatial and temporal distribution patterns of
exotic invasive plants in Kentucky. This research is designed to gain an overall picture of exotic invasive plants in the state of Kentucky and identify the historical distributions of typical exotic invasive species in Kentucky. 24-year weed identification forms from University of Kentucky Weed Science Identification Program (UKWSIP) were used to survey exotic invasive plants in Kentucky. Spatial and temporal distribution maps for the top 10 most reported invasive plants were created and the predominant land use type for each of these top 10 species was determined according to collection records. To estimate the long-time historical distribution, we also collected records from 15 herbaria in Kentucky. Together with the UKWSIP data, herbaria collections dating back to 1870s revealed the historical distributions of 16 typical exotic invasive plants in Kentucky. The cumulative number of total occupied counties was used to determine the distribution rate for each species. Knowledge gained from this project may help to prevent invasions and mitigate the impact of exotic invasive weeds, producing long-term social, ecological, and economic benefits.
Invasive species is a significant problem in many ecosystems, reaching epidemic proportions and resulting in significant ecologic and economic losses. Our ability to prevent and/or mitigate invasive species is in part hindered by insufficient knowledge of spatial distribution and spread of invasive species in ecosystems that have been challenged. In this study, we demonstrate the use of existing voluntary data to survey invasive plant species in Kentucky. Data used in this study was collected through the University of Kentucky Weed Science Identification Program (UKWSIP) which provides a weed identification service for the public through the local county Cooperative Extension Offices across the state. Distribution maps for the top 10 most reported invasive plants were reconstructed to understand their distribution patterns. Predominant land use type for each of these ten invasive species was determined by comparing proportion of associated land use type for each species with proportion of each land use type for the overall records. We found that Kentucky is facing a large threat from exotic invasive weeds. We believe the invasive weeds, both in number of species, as well as frequency, were underestimated because our data is on a voluntary base. The distribution maps for the top 10 invasive species recorded indicated Kentucky was likely to be the southern invasion front for Canada thistle and Japanese knotweed, and the northern invasion front for Japanese stiltgrass and sericea lespedeza. Knowledge gained from this project will help to prevent and mitigate the impact of exotic invasive weeds in Kentucky and beyond.
INTRODUCTION

Exotic plant invasions have gained increasing attention globally due to their substantial ecological impacts and dramatic economic cost. The loss of biodiversity that invasive exotic species cause, along with other factors such as climate change, may decrease the resilience of an ecosystem to natural disturbance and disease (Callaway and Maron 2006; Manchester and Bullock 2000). To stop or mitigate the invasion of existing and new emerging species, an effective Early Detection and Rapid Response (EDRR) system is needed to detect the occurrence of invasions (Chornesky et al. 2005; Wittenberg and Cock 2001). EDRR systems help to identify the potential priority species list, provide adequate and timely information of species distribution patterns to decision-makers and the general public, and determine at-risk sites by utilizing predictive models (Chornesky et al. 2005; Lodge et al. 2006; Ries et al. 2004). In EDRR systems, identifying spatial explicit distribution patterns of invasive species in regions outside their native range is a fundamental component of their functions (Hulme 2006). The spatial distribution pattern of invasive plants may help to either predict the species distribution for a site, or further our understanding of factors that influence these distributions (Higgins et al. 1999). This information is also essential for planning eradication, containment, and control strategies of invasive species.

A common limitation of EDRR systems is that they have insufficient power to detect the significant change in distribution of invasive species due to limited sites sampled (Van Strien et al. 1997). However, sampling more sites to increase the power of surveys is often impractical because it needs enormous manpower and resources. Recently, researchers have begun to explore applications of remotely sensed imagery (e.g., satellite imagery and aerial photography) for identifying the distribution or impacts of invasive
exotic species (Cuneo et al. 2009; Huang and Asner 2009; Kimothi et al. 2010; Wilfong et al. 2009). These geospatial technologies can reduce costs and increase the efficiency and effectiveness of weed management programs for certain weeds (Wilson et al. 2008). However, many invasive plant species are not good candidates for remote sensing because they are indistinguishable from other native plants, particularly during vegetative growth (D'Iorio et al. 2007; Kimothi et al. 2010). On the other hand, some studies try to infer temporal dynamics using historical records, such as herbarium or museum collections (Chauvel et al. 2006; Graham et al. 2004; Lavoie et al. 2007). Success of these studies varied depending on the availability of the data. Utilizing existing voluntary data or initiating citizen scientist may provide a less costly approach and strengthen the likelihood of predicting trends of exotic invasions by providing more observed data with minimal cost (Engler et al. 2004). Several regional systems, such as Early Detection and Distribution Mapping System (EDDMapS, http://www.eddmaps.org) created by Southeast Exotic Pest Plant Council (SE-EPPC), Invasive Plant Atlas of New England (IPANE, http://www.ipane.org) and Invasive Plant Atlas of MidSouth (IPAMS, http://www.gri.msstate.edu/ipams/), have taken the advantage of the citizen scientist approach. The development and utilization of the voluntary data system can add a new catalyst for understanding natural phenomenon by offering more sample data, yet its application in a natural resource system is limited (Orr et al. 2007).

In this study, we demonstrate the use of existing voluntary data from the University of Kentucky Weed Science Identification Program (UKWSIP) to survey invasive species in Kentucky. We also reconstructed the spatial and temporal distribution maps of the top 10 most reported invasive species and determined their predominant habitat types.
Knowledge gained from this project will help to prevent and mitigate the impact of exotic invasive weeds, which will have long-term social, ecological, and economic benefits.

MATERIALS AND METHODS

Data collected through the UKWSIP from 1986 to 2009 were used in this study. The UKWSIP identifies weedy plants for the public and provides weed control recommendations in support of the county offices of the Cooperative Extension Service throughout Kentucky. Since 1986, weed identification forms have been used to generate written records pertaining to information on each plant specimen submitted for identification. Slight modifications have been made during the last 24 years, but, in general, identification forms have the following associated information: submitter’s contact information, date, county, habitat associated with the collected specimen, and species name and control recommendation. A total of 8,289 weed identification forms collected across Kentucky were used in this study. All records were digitized into a database including the following key fields: collection date, collection county, associated land use type, scientific name, and common name of the submitted specimen. Records with imprecise or incomplete information were excluded from further analyses.

In this study, we only focused on plants considered to be invasive exotic weeds. There are many invasive exotic species lists available both at the state and national level. To ensure local relevance, we consider a weed as an invasive exotic weed if it is listed as an invasive exotic species by the Kentucky Exotic Pest Plant Council (KY-EPPC; http://www.se-eppc.org/ky/list.htm). Nomenclature was unified through the database following the Kentucky Exotic Pest Plant Council list. Statistical summaries were
generated to infer the status of invasive exotic weeds in Kentucky, including total number of invasive exotic weeds, the most frequently reported invasive species and families, the most wide spread species, and counties with the most invasive species reported. We also conducted regression analysis to determine if an association existed between human population and the total number of invasive species in each county.

Second, information from the exotic invasive weed database was used to create distribution maps. Year and county of each collection were used to define the time and location of the presence of a given invasive species. To illustrate spatial pattern, tabular records of invasive species were first attributed to different counties in ArcGIS 9.3 (ESRI, Inc. Redlands, CA) based on the location information of samples. The earliest record for a given invasive species in each county was used to represent its spatial dynamic. This means counties once occupied by a given invasive species were defined as permanently “infested” by this species. To ensure sufficient data to understand the invasion pattern, only the top 10 most frequently reported exotic invasive weeds were mapped (Table 2.1). Distribution maps generated from our database were then overlapped with maps from USDA PLANTS database (USDA NRCS 2010) and EDDMapS (2010) in Kentucky and adjacent states. By combining these geographic distributions, we inferred whether Kentucky was located on the edge of the current overall range of a given weed. If it was, then Kentucky was likely to be the invasion front of this specific invasive weed.

Associated land use types in the database were used to determine the predominant land use type for each of the top 10 invasive species. Because land use type categories on the weed identification forms were slightly different in various time periods, we
recategorized land use type into eight groups: Cropland, Pasture and Hayfields, Lawn/Turf, Non-Cropland, Ornamental, Trees/Woodlot, Vegetable/Garden, and Others (e.g., aquatic and roadside). The Cropland group was further divided into sub-categories for additional analysis. To detect the invasive species predominant habitat, a total of 6483 records with explicit land use type were used to estimate the average proportion of each land use type group. Proportion of associated land use type for each species was then compared with the overall average proportion of each land use type in order to eliminate some biases inherent in herbarium data by reducing the effect of collecting effort. For example, although 35% records of Japanese knotweed (*Polygonum cuspidatum* Siebold & Zucc.) were collected in Lawn/Turf land use type, we can’t confirm this invasive weed is highly associated with this habitat because 32% of the UKWSIP records were collected in Lawn/Turf (Table 2.3). If a given land use type for a specific invasive exotic species has more than twice the percentage than average proportion, this land use type was considered as the predominant habitat for this given invasive species. Based on the 928 records with Cropland land use type, a similar process was also implemented for the sub-categories under the Cropland group to find the predominant crop type for the top 10 invasive species.

RESULTS

**Overview of Invasive Weeds in Kentucky**

Based on our survey, Kentucky is facing a large threat from exotic invasive weeds. A total of 79 different exotic invasive weed species were reported 1,488 times during the 24 year time period (1986-2009) in Kentucky, covering 86% of the invasive plant species on
The top ten most frequently reported invasive exotic weeds were ground ivy (*Glechoma hederacea* L.), Japanese knotweed (*Polygonum cuspidatum* Sieb. & Zucc.), common lespedeza (*Kummerowia striata* (Thunb.) Schindl.), annual bluegrass (*Poa annua* L.), common chickweed (*Stellaria media* (L.) Vill.), sericea lespedeza (*Lespedeza cuneata* (Dumont) G. Don), Star-of-Bethlehem (*Ornithogalum umbellatum* L.), barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.), Canada thistle (*Cirsium arvense* (L.) Scop.), and Japanese stiltgrass (*Microstegium vimineum* (Trin.) A. Camus) (Table 2.1). The majority of the invasive plants were herbaceous (68 spp.), followed by shrubs and trees (7 and 4 spp., respectively). All 79 invasive species reported through the UKWSIP belong to 31 families. Twenty-three percent of these invasive exotic species are from the *Poaceae* family (18 species), the highest among all families, followed by the *Fabaceae*, *Asteraceae*, and *Lamiaceae* families (9, 5, and 5 species, respectively) (Table 2.2). The rest of the families have four species or less, 18 families each has only one invasive exotic weed.

The number of invasive exotic species reported was the highest right after written records were kept through the weed science identification program in 1986, and decreased as time went by. In the first four years (1986-89), 49 invasive species (62%) were reported in 74 counties (Figure 2.1a). In the next 10 years (1990-99), 23 new species were reported. After 2000, only seven species have been added to the database.

Exotic invasive weeds have been widely reported across Kentucky. All counties had at least one exotic invasive species reported except for four counties (Figure 2.1b). Fayette County, where Lexington, the second largest city in the Commonwealth is located, had the most number of invasive exotic weed species (33) and contributed the most weed
Spatial and Temporal Distribution of the Top 10 Invasive Weeds

Spatial and temporal distribution maps created in our study revealed a clear pattern of the top 10 exotic invasive weeds distribution. By comparing our database with EDDMapS and PLANTS database, we found that Kentucky was likely to be the invasion front for Canada thistle, Japanese stiltgrass, Japanese knotweed, and sericea lespedeza (Figure 2.2). Canada thistle had invaded many states north of Kentucky (Figure 2.2a). Our distribution map showed it was concentrated in the triangle area among Louisville, Lexington, and Covington in northern Kentucky. Most recent reports of this weed were mainly from the southern part of the state. The overall distribution indicates that southern Kentucky is likely to be the current invasion front for Canada thistle. Japanese stiltgrass was first introduced into Tennessee around 1919 (Fairbrot.De and Gray 1972b). It currently exists across Tennessee and Virginia and also occupies the eastern and western portion of Kentucky according to EDDMapS and PLANTS database (Figure 2.2b). Our data filled the gap between the east and west while records from northern Kentucky were absent, which indicates northern Kentucky is likely to be the invasion front for Japanese stiltgrass. The distribution of Japanese knotweed was quite patchy, with most populations being concentrated in the central and east of Kentucky (Figure 2.2c). As indicated by our
data, this species was widely distributed across Kentucky with a possible invasion front at the southwestern portion of the state. Sericea lespedeza was prevalent across Kentucky with a potential invasion front in northern Kentucky (Figure 2.2d).

The other six species are distributed widely in Kentucky and adjacent states. New localities were reported simultaneously in different regions of the state (Figure 2.3). As time passed by, these exotic weeds were then reported in surrounding counties from an early location in a concentric candlewick pattern. Ground ivy was only reported in central and northern Kentucky in EDDMapS and PLANTS database. Our data gave evidence that this weed was also reported in other areas, which indicated ground ivy is prevalent throughout Kentucky (Figure 2.3b). Star-of-Bethlehem and common chickweed were not limited to a particular region of the state (Figure 2.3c, 2.3d). EDDMapS and PLANTS database reported that annual bluegrass and barnyardgrass were scattered across the states around Kentucky except for Ohio (Figure 2.3e, 2.3f). Our data further suggested that these two weeds were currently prevalent across Kentucky. None of the above invasive weeds was reported frequently in any particular region of the state.

**Predominant Land Use Type for the Top 10 Invasive Weeds**

The majority of the weeds reported in this database were from areas with high levels of human impact. Three quarters of the invasive weeds reported were from Lawn/Turf areas (32%), Pasture and Hayfields (32%), and Cropland (14%) habitats. Trees/Woodlot habitat contributed less than one percent of the total case, which made it the rarest land use type in our study. Each of the top 10 invasive weeds was associated with a dominant land use type. Compared with the land use proportion from all records, ground ivy,
common lespedeza, and annual bluegrass were more frequently found in Lawn/Turf land use areas (Table 2.3). Japanese knotweed, common chickweed, sericea lespedeza, and star-of-Bethlehem were primarily found on Non-cropland, Vegetable/Garden, Pasture and Hayfields, and Ornamental land use types, respectively. Whereas, barnyardgrass and Canada thistle had high proportions in Cropland land use types. Although Japanese stiltgrass had a high proportion in Trees/Woodlot, we can’t confirm it had a strong habitat type preference because it had only two samples. In the subcategory of Cropland, Annual bluegrass and barnyardgrass showed preference for wheat and soybean habitat, respectively (Table 2.4).

DISCUSSION

Kentucky is facing a large threat from exotic invasive weeds. Seventy-nine declared invasive plants from Kentucky Exotic Pest Plant Council’s list have been reported through the UKWISP from 116 counties across Kentucky during the last 24 years. We believe the invasive weeds, both in number of species, as well as frequency, were underestimated because the weed identification service is on a voluntary base. Samples were submitted by individuals through the local county Cooperative Extension Service and forwarded to the UK Weed Science program. One example to support this point is that kudzu (Pueraria montana var. lobata (Willd.) Maesen & S.M. Almeida) was only reported once in our entire dataset. The likely explanation for the low reports number of kudzu is that it is already well known as an exotic invasive species whereby either the individual or the local county agent was able to identify.

Generally, after the initial introduction of an invasive species, the pattern of invasion
begins with a lag period of few collections followed by a period of rapid, exponential expansion. Alien invasive species recently studied in France (Chauvel et al. 2006), Quebec (Lavoie et al. 2007), and North America (Barney 2006) follow the same temporal invasion pattern. Sixty-three percent of the invasive species were reported in the first four years since the earliest records, which indicates these invasive plants have been in Kentucky for more than 20 years. Further research about how long these invasive species have been in Kentucky can be studied base on older records from herbaria or museums.

There is no significant correlation between population and occurrence of invasive species based on our records. But, we still need to take into account the effect of local county extension agents on the diversity and frequency of weed reports (Crawford and Hoagland 2009). We suspect that we had more samples submitted for weed identification from some counties than others partly because either the county extension agents in those counties are less familiar with identifying and control of unwanted plants and forward these samples for identification, or there are more people in those counties submitting samples. It may depend on the specific plant species as to whether or not it is reported frequently. Such submissions should be decreased as specific weeds become familiar for the extension agents and the public. Other institutions offering similar plant identification service such as botanical gardens might also have received weed reports which was not included in our database. This may result in the lack of weed reports in the two east counties, Pike and Martin because they may submit weed to the institutions in Virginia for identification. In addition, we referenced the KY-EPPC list to define the invasive species in our study, which does not include all invasive species. More species would be recognized as invasive species if we referenced other regional or national invasive
species databases. Additional studies by referencing other invasive species databases would bear their own significances.

Maps of plant distributions based on records from the UKWSIP, along with the other two voluntary data, EDDMapS and PLANTS database, gave us a reasonably accurate picture of the current distribution of a given invasive species within Kentucky. Baker (1974) described the typical North American invasion pattern to be scattered populations expanding to fill in absences between populations. The distributions of the top 10 invasive alien weeds in our study appear to follow this pattern. Plant distribution maps will be more accurate as the number of plant collections increases. Given the short history of the weed records embodied in the current weed identification system and the limitations on how samples are submitted, analysis of the change in species distribution over time can be somewhat unreliable. However, weed identification data still contributed to sketching a big picture of current distribution of alien weeds. A good illustration is that four of the top 10 species distribution maps indicate Kentucky was likely to be the southern invasion front for Canada thistle and Japanese knotweed, and the northern front for Japanese stiltgrass and sericea lespedeza (Figure 2.2). Plus, our voluntary data provided more details for the exotic invasive weed distribution by filling the gaps of other weed detection systems such as EDDMapS.

It’s not surprising that most of the weed reports were submitted from human related land use types since this weed identification program was designed to detect weeds in urban and agriculture areas where invasive species more likely gain attention from people. Ground ivy, common lespedeza, and annual bluegrass have been reported as common weeds in lawn turf (Busey 2003; Kohler et al. 2004b), and sericea lespedeza is
considered an usual invasive weed in the tall grass prairies of the Southern Great Plains (Koger et al. 2002). Common chickweed is often found in gardens and arable areas (Briggs et al. 1991). In additional, previous studies have reported that annual bluegrass and barnyardgrass prefer wheat and soybean field, respectively (Borovickova 1992; Vail and Oliver 1993; Wilson 1981). The associated habitats for the top 10 species revealed in our study can assist in identifying the predominant land use/habitat type(s) of a given invasive species, which helps natural resource managers to concentrate limited resources to habitats that are highly susceptible to certain invasive species. It can also facilitate the prediction of the spread of exotic invasive weeds by identifying the potential invasion area.

The data resource we used has both strengths and weaknesses. The advantages involve the nature of the source of weed identification database. It allows reports to be submitted from more extensive areas in a shorter time, which is more economical and efficient than herbarium collections and extensive field surveys. The disadvantages include the bias for all such plant records, the nonrandom sampling bias, which is caused by factors such as: unequal sampling effort over time and non-random geographical representation. Poor location information in the specimens and incorrect identification may reduce the accuracy of result. Since Kentucky’s forests cover 47 percent of the State (Forest inventory 2004), the concentration on a particular urban and agriculture related group of plants in this study may produced underrepresentation of forest related invasive plants. Overall, these biases may lead to inadequate reports, resulting in both underestimation of invasive species occurrence and disproportionately representation.

Our study suggests that weed identification system can be a valuable data resource to
reconstruct the historic distribution patterns of invasive species. It can help to fill gaps of other invasive database such as EDDMapS and improve the accuracy of exotic invasive species distribution maps. Similar weed identification services already exist in other states. The wide application of these systems in invasive species EDRR systems will greatly enhance our ability to combat exotic invasion.

The knowledge gained from this study would provide timely information to policy makers in Kentucky and throughout the Southeast region in support of effective policy development. The invasive species report frequency generated from our database could be used to identify the priority invasive plant list. With predictive models, distribution maps and habitat associations of given invasive species could help to determine at–risk sites and to concentrate limited resource on the potential vulnerable areas to prevent future invasion of exotic species. The UKWSIP forms could also reveal new exotic invasive species which are not included in the KY-EPPC list so as to increase policy makers and public awareness of new exotic species invasion.
Table 2.1 The top 10 most frequently reported invasive exotic weeds in University of Kentucky Weed Science Identification Program (UKWSIP) since 1986.

<table>
<thead>
<tr>
<th>Weed Species</th>
<th>Common Name</th>
<th>Total Reports</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Glechoma hederacea</em> L.</td>
<td>ground ivy</td>
<td>99</td>
</tr>
<tr>
<td><em>Polygonum cuspidatum</em> Sieb. &amp; Zucc.</td>
<td>Japanese knotweed</td>
<td>91</td>
</tr>
<tr>
<td><em>Kummerowia striata</em> (Thunb.) Schindl.</td>
<td>common lespedeza</td>
<td>86</td>
</tr>
<tr>
<td><em>Poa annua</em> L.</td>
<td>annual bluegrass</td>
<td>83</td>
</tr>
<tr>
<td><em>Stellaria media</em> (L.) Vill.</td>
<td>common chickweed</td>
<td>77</td>
</tr>
<tr>
<td><em>Lespedeza cuneata</em> (Dumont) G. Don</td>
<td>sericea lespedeza</td>
<td>62</td>
</tr>
<tr>
<td><em>Ornithogalum umbellatum</em> L.</td>
<td>star-of-Bethlehem</td>
<td>57</td>
</tr>
<tr>
<td><em>Echinochloa crus-galli</em> (L.) Beauv.</td>
<td>barnyardgrass</td>
<td>57</td>
</tr>
<tr>
<td><em>Cirsium arvense</em> (L.) Scop.</td>
<td>Canada thistle</td>
<td>53</td>
</tr>
<tr>
<td><em>Microstegium vimineum</em> (Trin.) A. Camus</td>
<td>Japanese stiltgrass</td>
<td>51</td>
</tr>
</tbody>
</table>
Table 2.2 Number of species within each family reported within the Kentucky Weed Science Identification Program.

<table>
<thead>
<tr>
<th>Number of species</th>
<th>Family name</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>Poaceae</td>
</tr>
<tr>
<td>9</td>
<td>Fabaceae</td>
</tr>
<tr>
<td>5</td>
<td>Asteraceae, Lamiaceae</td>
</tr>
<tr>
<td>4</td>
<td>Polygonaceae</td>
</tr>
<tr>
<td>3</td>
<td>Brassicaceae, Celastraceae, Convolvulaceae, Rosaceae</td>
</tr>
<tr>
<td>2</td>
<td>Apiaceae, Caprifoliaceae, Chenopodiaceae, Liliaceae</td>
</tr>
<tr>
<td>1</td>
<td>Apocynaceae, Araliaceae, Boraginaceae, Caryophyllaceae, Clusiaceae, Commelinaceae, Dioscoreaceae, Dipsacaceae, Elaeagnaceae, Lardizabalaceae, Moraceae, Oleaceae, Oxalidaceae, Ranunculaceae, Salicaceae, Scrophulariaceae, Simaroubaceae, Solanaceae</td>
</tr>
</tbody>
</table>
Table 2.3 Percentage of major land use type associated with the top 10 invasive exotic weeds reported in UKWSIP. The number with an asterisk (*) represents this land use type has more than twice of percentage than average.

<table>
<thead>
<tr>
<th>Weed Species</th>
<th>Records (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lawn/Turf</td>
</tr>
<tr>
<td><em>Glechoma hederacea</em></td>
<td>65 (81*)</td>
</tr>
<tr>
<td><em>Polygonum cuspidatum</em></td>
<td>22 (35)</td>
</tr>
<tr>
<td><em>Lespedeza striata</em></td>
<td>59 (82*)</td>
</tr>
<tr>
<td><em>Poa annua</em></td>
<td>48 (72*)</td>
</tr>
<tr>
<td><em>Stellaria media</em></td>
<td>38 (57)</td>
</tr>
<tr>
<td><em>Lespedeza cuneata</em></td>
<td>1 (2)</td>
</tr>
<tr>
<td><em>Ornithogalum umbellatum</em></td>
<td>30 (58)</td>
</tr>
<tr>
<td><em>Echinochloa crus-galli</em></td>
<td>3 (7)</td>
</tr>
<tr>
<td><em>Cirsium arvense</em></td>
<td>1 (2)</td>
</tr>
<tr>
<td><em>Microstegium vimineum</em></td>
<td>19 (49)</td>
</tr>
<tr>
<td>Total UKWSIP records</td>
<td>2079 (32)</td>
</tr>
</tbody>
</table>
Table 2.4 Percentage of predominant Cropland type associated with the top 10 invasive exotic weeds reported in UKWSIP. The number with an asterisk (*) represents this land use type has more than twice of the number of case than average.

<table>
<thead>
<tr>
<th>Weed species</th>
<th>Corn</th>
<th>Soybean</th>
<th>Tobacco</th>
<th>Wheat</th>
<th>Other</th>
<th>Total case</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Glechoma hederacea</em></td>
<td>0 (0)</td>
<td>2 (100)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>2</td>
</tr>
<tr>
<td><em>Polygonum cuspidatum</em></td>
<td>4 (67)</td>
<td>1 (17)</td>
<td>1 (17)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>6</td>
</tr>
<tr>
<td><em>Kummerowia striata</em></td>
<td>0 (0)</td>
<td>1 (100)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>1</td>
</tr>
<tr>
<td><em>Poa annua</em></td>
<td>3 (30)</td>
<td>1 (10)</td>
<td>1 (10)</td>
<td>5 (50*)</td>
<td>0 (0)</td>
<td>10</td>
</tr>
<tr>
<td><em>Stellaria media</em></td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0</td>
</tr>
<tr>
<td><em>Lespedeza cuneata</em></td>
<td>0 (0)</td>
<td>1 (100)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>1</td>
</tr>
<tr>
<td><em>Ornithogalum umbellatum</em></td>
<td>3 (50)</td>
<td>1 (17)</td>
<td>1 (17)</td>
<td>1 (17)</td>
<td>0 (0)</td>
<td>6</td>
</tr>
<tr>
<td><em>Echinochloa crus-galli</em></td>
<td>2 (14)</td>
<td>9 (64*)</td>
<td>1 (7)</td>
<td>0 (0)</td>
<td>2 (14)</td>
<td>14</td>
</tr>
<tr>
<td><em>Cirsium arvense</em></td>
<td>9 (56)</td>
<td>2 (13)</td>
<td>4 (25)</td>
<td>1 (6)</td>
<td>0 (0)</td>
<td>16</td>
</tr>
<tr>
<td><em>Microstegium vimineum</em></td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total UKWSIP records</strong></td>
<td>334 (36)</td>
<td>272 (29)</td>
<td>160 (17)</td>
<td>120 (13)</td>
<td>42 (5)</td>
<td>928</td>
</tr>
</tbody>
</table>
Figure 2.1 County level spatial distribution of invasive exotic weeds by (a) year first reported, (b) total number of invasive species reported based on KY-EPPC list, (c) report frequency based on UKWSIP database, and (d) the Kentucky population density (2000 Census data).
Figure 2.2 Spatial distribution of (a) Canada thistle (*Cirsium arvense*), (b) Japanese stiltgrass (*Microstegium vimineum*), (c) Japanese knotweed (*Polygonum cuspidatum*) and (d) sericea lespedeza (*Lespedeza cuneata*) at the county level. The strip shadow represents weed distribution based on EDDMapS data and PLANTS database. Different solid shadings indicate weed spread in different periods based on weed identification data.
Figure 2.3 Spatial distribution of (a) common lespedeza (*Kummerowia striata*), (b) ground ivy (*Glechoma hederacea*), (c) star-of-Bethlehem (*Ornithogalum umbellatum*), (d) common chickweed (*Stellaria media*), (e) annual bluegrass (*Poa annua*), and (f) barnyardgrass (*Echinochloa crus-galli*) at the county level. The strip shadow represents weed distribution based on EDDMapS and PLANTS database. Different solid shadings indicate weed spread in different periods based on weed identification data.
CHAPTER THREE: The Historical Distribution of Sixteen Exotic Invasive Species in Kentucky based on Herbarium Records

SUMMARY

Regional distribution and abundance data for invasive plant species are urgently needed for planning the management of invasive species, modeling of invasion risks and impacts, and communicating the scope of the problem. Yet, detailed regional distribution data are rare. In this project, historical distributions of 16 exotic invasive species in Kentucky were reconstructed based on records from 15 Kentucky herbaria. Sampling locations and dates were used to reveal the historical spatial distributions. The date of the first recorded collection in each county was identified and the expansion pattern for each species was examined. The majority of the invasive species in this study were first reported in multiple locations over 50 years ago. The present distribution shows that the majority of these 16 invasive species are scattered throughout Kentucky, indicating no concentrations in particular regions. The cumulative curves for all species fitted a “J” shape expansion curve, indicating the potential for further invasion in the future. This study demonstrates the usefulness of herbarium data to estimate the distribution of invasive species and to test hypothesis about their historical dynamics. Spatially explicit knowledge gained from this study can aid natural resource managers to prevent and/or mitigate biological invasion of exotic species.
INTRODUCTION

The introduction and spread of exotic invasive species into human-influenced and natural environments has garnered increasing attention globally. The biology of invasive species has attracted the interest of ecologists and conservation biologists (Ruiz and Carlton 2003; Vila and Weiner 2004; Westbrooks et al. 1998; Wu et al. 2005). In spite of the many studies that have been conducted, little is known regarding regional historical dynamics of successful exotic species invasion (Callaway and Aschehoug 2000). Indeed, increased human mobility over the past 100 years and the modification of the biosphere has exposed disturbed habitats to invasive species and altered community structure and ecosystem processes (Callaway and Maron 2006; Manchester and Bullock 2000).

Recently, the spatial distribution of exotic invasive species has become a hot topic (Christen and Matlack 2009; Kelly et al. 2009; Liu et al. 2005; Merriam 2003). As reported by Strayer et al. (2006), however, most invasive species studies have lacked a temporal context, which can lead to unreliable or even controversial results. Long-term data is needed to understand the attributes of the invasion process. To understand the historical distribution of non-indigenous species, many researchers are turning to physical or online herbarium collections (Lavoie et al. 2003; Lindgren 2003; Miller et al. 2009; Wu et al. 2005; Zangerl and Berenbaum 2005). Although the data from herbarium specimens suffer from several biases, they constitute a valuable source of information to document the early stages of the invasion process (Crawford and Hoagland 2009; Lavoie et al. 2007). Plant specimens stored in herbaria are numerous and usually well preserved. Furthermore, most herbarium specimens have informative labels which indicate sampling location, date, and the habitat type in which the plant was collected.

Currently, the Commonwealth of Kentucky is facing a significant threat from exotic
species invasion to its natural ecosystems. According to Jones (2005), nearly 25 percent of vascular plants in Kentucky are non-indigenous. Kentucky Exotic Pest Plant Council (KY- EPPC; http://www.se-eppc.org/ky/list.htm) also lists 92 plant species as threats to local communities. Although research and extension programs to determine management strategies exist in this region, no major effort exists for identifying temporal and spatial distribution patterns of exotic invasive species. This paper describes the historical distribution of 16 representative exotic invasive species in tree, shrub, vine, and herb groups (Table 3.1) from the time of first recorded observation to the present status in Kentucky. The historical distribution of each species was reconstructed using plant specimens found in 15 herbaria in or around Kentucky dating back to 1870s (Appendix Table 3.A). The cumulative number of total occupied counties was used to determine the distribution rate for each species. The focus of this study is the utility of herbarium data for the reconstruction of spatial and temporal distribution patterns of exotic invasive species and the identification of factors contributing to the invasion of these exotic species.

MATERIALS AND METHODS
This study is based exclusively on herbarium specimens from 15 sources (herbaria, botanical gardens or databases of online herbaria; see Appendix Table 3.A) in and around Kentucky. Since these herbaria have numerous exotic invasive plant specimens, only 16 typical species representing various growth forms and regions were included in this study. The sampling location and year of collection of each invasive species specimen was identified as precisely as possible. Due to the variability of spatial information
provided on herbarium specimen labels, all sampling locations were specified to county level. Specimens of the same year and location were treated as one record. Nomenclature in this study follows the Kentucky Exotic Pest Plant Council list. Specimens having incomplete or imprecise information about the sampling location or collection date were excluded from further analysis.

To reconstruct the historical distribution of exotic invasive species in Kentucky, specimens in the resulting dataset were georeferenced and mapped using ArcGIS 9.3 (ESRI, Inc. Redlands, CA) with the time attributes attached. Because of the long duration of herbarium records, a temporal resolution of one year was used. For each invasive species, the earliest collection in each county was used to represent its temporal dynamic. Historical distribution maps for each species were reconstructed at six time periods, starting with the first record, to depict the spread of the species through time. In order to compare the distribution rate of invasive exotic species introduced over time, we categorized all invasive species based on the year they were first reported into three groups: 1878-1909, 1910-1941, and 1942-1973. Distribution rates for invasive species were estimated using cumulative numbers of total occupied counties through time based on herbaria specimens and compared among three groups.

RESULTS

Herbaria specimens

There were a total of 2,233 specimens of the 16 exotic invasive plants in this study kept in the 15 Kentucky herbaria. Several of these invasive species dated back 100 years (Table 3.1). The earliest collection was a specimen of princess-tree (*Paulownia tomentosa*)
(Thunb.) Sieb. & Zucc. ex Steud. ) found in Fayette county in 1878. Common Reed
(*Phragmites australis* (Cav.) Trin. ex Steud.) was one of the more recent invasive species
within the herbarium collections (1973) in Kentucky. Based on herbaria specimens,
Japanese honeysuckle (*Lonicera japonica* Thunb.) was found in 100 counties across
Kentucky, which made it the most widespread invasive species in this study, whereas, the
presence of common reed was only recorded in 11 counties. The majority of the 16
invasive species were currently found throughout Kentucky (Figure 3.4, 3.5, 3.7-10,
Appendix Figure 3.C-I). The exceptions were Amur honeysuckle (*Lonicera maackii*
(Rupr.) Herder), which was restricted to northern and central Kentucky, kudzu (*Pueraria
montana* var. *lobata* (Willd.) Maesen & S.M. Almeida), which was limited to southern
Kentucky, and common reed, which was limited to western Kentucky (Figure 3.1-3). The
Herbarium at Eastern Kentucky University contributed 489 specimens, the biggest
collection among 15 institutions. The specimens from each herbarium were mainly
collected in the regions where herbarium located except for University of Kentucky
Weed Science Identification program whose collections cover most of the state (App.
Figure 3A, 3B). The detailed information on herbaria specimens was shown in Appendix
Table 3B.

**Historical distribution**

The maps generated from herbaria specimens indicated that the majority of the 16
invasive species illustrated no discernible spatial invasion or expansion pattern. However,
the historical distribution maps of Amur honeysuckle and tree-of-heaven (*Ailanthus
altissima* (P. Mill.) Swingle) suggested that each of these two species may have been
introduced in different regions of Kentucky simultaneously (Figure 3.1, 3.4). Based on
the historical distribution maps, tree-of-heaven was first found in western, central and
eastern Kentucky separately at an early time period (Figure 3.4). During the following
years, specimens of this species were generally collected in neighboring counties near the
first colonies. It suggested that the original invasion in western Kentucky was responsible
for the subsequent invasion in western Kentucky, while the central colonies accounted for
the invasion in central Kentucky. The first few collections of Amur honeysuckle were
found in central and northern Kentucky (Figure 3.1). Subsequent specimens were
collected in the surrounding counties of original colonies over the next 20 years.
Thereafter, these two separate colonies connected around 1997 and afterward spread
further. We also found that common reed and Japanese stiltgrass (*Microstegium
vimineum* (Trin.) A. Camus) were introduced in one particular region and then spread
from that area (Figure 3.3, 3.5). Specimens of common reed were first collected in 1973
in western Kentucky (Figure 3.3). After that, subsequent colonies of this species were
only found nearby, except for Kenton county in northern Kentucky. Somewhat
differently, Japanese stiltgrass was first introduced into Knoxville, TN in 1919 and was
first reported in Kentucky near the southeast border in 1931 (Figure 3.5). Referring to the
historical distribution map generated, the spread of this species was scattered throughout
Kentucky, however, it showed a remarkable invasion trend from southeast to northwest.

**Distribution rate**

Our data suggest the majority of invasive plants have few collections at their early
invasion period, and experienced a rapid expansion after that. The cumulative distribution
of occupied counties for all invasive species fitted a “J” shape curve. We found invasive species first reported between 1910 and 1941 generally invaded more quickly than species introduced in earlier or later time periods (Figure 3.6). Four species first reported from 1929 to 1936, Japanese knotweed (*Polygonum cuspidatum* Sieb. & Zucc.), Japanese stiltgrass, sericea lespedeza (*Lespedeza cuneata* (Dumont) G. Don), and multiflora rose (*Rosa multiflora* Thunb. ex Murr.), expanded to a wider range than most alien species found in Kentucky before 1910. The other two alien species in this group, climbing euonymus (*Euonymus fortunei* (Turcz.) Hand.-Maz.) and autumn olive (*Elaeagnus umbellata* Thunb.), occupied similar ranges to invasive plants that arrived in Kentucky at an earlier time, indicating a faster rate of spread. All invasive species introduced before 1910 showed a constant increase over time except for Japanese honeysuckle. In addition, the cumulative curves of occupied counties suggested no similarity among invasive species first collected after 1942.

**DISCUSSION**

Herbarium specimens are an important source of information for reconstructing the introduction and colonization of a species (Barney et al. 2008; Chauvel et al. 2006; Lavoie et al. 2007). For example, Dessaint et al. (2005) used herbarium collections to study the historical distribution of ragweed (*Ambrosia artemisiifolia* L.) in France. Information from herbarium collections now became available on the internet, and can be used to answer a wide range of ecological questions (Graham et al. 2004). Temporal and geographical biases can exist in herbarium collections (Delisle et al. 2003). A temporal bias may be present because of irregular collecting intensity. Collection intensity can
decline once the species is considered well represented in herbaria collections. But we can still assume herbarium observations approximate the distribution of an invasive species since the first specimens of most species investigated in this study can be traced back to the beginning of last century, close to the time at which these species were first recorded in North America. A geographical bias might be present because of non-random geographical representation. The species sampled in herbaria usually reflect the flora of a specific geographical area. Analysis of herbarium collections can potentially underestimate the current range of invasive species and thus, the magnitude of their ecological impact.

Using information provided by historical distribution maps of invasive species, we can examine the invasion pattern and suggest explanations for the spread of these invasive species. All exotic invasive plants in this study were introduced more than half a century ago except for common reed, which was first reported in 1973 (Table 3.1). Initial specimens of 7 invasive species were first collected more than 100 years ago. For most species, the spatial and temporal distribution in Kentucky showed no clear front: new locations separated by large distances were colonized simultaneously (Figure 3.2-4, 3.7-10, Appendix Figure 3.C-I). Each species was introduced in various locations at different periods of time, and spread in different directions.

We suggest a clear northwestward invasion pattern based on the historical distribution maps for Japanese stiltgrass (Figure 3.5). This invasive species was introduced in Knoxville, TN in 1919, as a packing material for porcelain (Kaufman and Kaufman 2007). According to the Early Detection and Distribution Mapping System (EDDMapS, 2010), the current distribution of this species was concentrated in Tennessee, Virginia,
and the western Carolinas. The first specimen of Japanese stiltgrass was collected in 1931 near the southeast boundary of Kentucky, which is adjacent to the original invasion site and only 12 years later than its first appearance in the United States (Figure 3.5). It was believed that these earlier colonies were responsible for the following northwestward invasion although new locations, separated from the earlier colonies, were detected. Recently, Flory (2010) reported the appearance of Japanese stiltgrass in southern Indiana, which further suggests this species is expanding in a northeastward direction. A previous study suggests that human disturbance, such as forest road management, is responsible for the rapid spread of this invasive species (Rauschert et al. 2010). Future studies to continue monitoring this species are needed to further confirm its spread north of Kentucky.

Historical invasion maps generated from herbarium specimens of Amur honeysuckle indicated a concentric circle candlewick pattern during the last 50 years (Figure 3.1). Amur honeysuckle was first introduced in central and northern Kentucky. During the following years, this exotic invasive species was generally found in areas surrounding the original occupied counties. Based on this invasion pattern, areas surrounded by the current range of Amur honeysuckle are potential vulnerable areas for invasion. This species has been used as an ornamental (Harris et al. 2009), so it is not surprising that Amur honeysuckle was mainly found near urban areas in central and northern Kentucky. Amur honeysuckle produces abundant fruit which are attractive to bird and small animals. Its appearance in rural areas may have resulted from seed dispersal by birds. The limited, distant distribution of this species in western and southern Kentucky can also be explained either by horticultural trade or the migration of birds. Overall, the distribution
pattern of Amur honeysuckle suggests human activity is responsible for the colonization of this invasive species and dispersal by fruit-eating birds and horticultural activity is the main cause of spread in this species.

The historical distributions of other species show no clear dispersal pattern during their spread. For example, princesstree was first reported in central Kentucky before 1910. A small number of specimens were collected in different regions of the state during the following 60 years (Figure 3.7). Till 1970, the distribution of princesstree had been scattered throughout the state. As time passed by, this invasive tree was generally reported in surrounding counties from an early location. The current distribution of princesstree were scattered throughout Kentucky, indicating no concentrations in particular regions.

The invasion patterns of kudzu (*Pueraria montana* var. *lobata* (Willd.) Maesen & S.M. Almeida), autumn olive, and common reed were primarily related to the fact that they had been used to prevent soil erosion, reclaim mine spoil, or help with water treatment (Batty and Younger 2004; Forseth and Innis 2004; Shields et al. 1995; Zipper et al. 2007). Only one specimen of kudzu was collected before 1930s in Kentucky (Figure 3.2). In the 1930s and 1940s, the Soil Conservation Service promoted kudzu for erosion control. After that, kudzu was commonly found scattered in distant regions of southern Kentucky. The U.S. government stopped advocating the use of kudzu in 1953 after they found this vine can also cause damage to the forests by preventing trees from obtaining sunlight. The USDA later declared kudzu to be a weed in 1972 (Forseth and Innis 2004). From then on, the established areas of kudzu in Kentucky expanded into surrounding counties at a relative slow rate because it is limited to vegetative expansion by rhizomes.
Autumn olive was introduced in Kentucky in 1939. Only one specimen of this species was recorded in the following 45 years (Figure 3.8). After the Surface Mining Control and Reclamation Act of 1977, it has been widely used for strip mine reclamation (Zipper et al. 2007). Based on herbaria specimens, its current distribution is spread across western and eastern Kentucky coal fields. Another invasive species, common reed, was mainly found in wetland habitat. It has been used for water treatment (Batty and Younger 2004). This trait of common reed can explain why the collections of common reed were generally restricted to wetlands in western Kentucky (Figure 3.3).

The spatial and temporal maps generated also suggest the present distribution of some species is limited by their suitable habitat. Kudzu grows best where summer temperatures are above 80º F, and winters are mild. This species was introduced in various points of southern Kentucky over 100 years ago. Currently, kudzu is still concentrated in the south which indicates the importance of latitude in limiting the spatial distribution of this species (Cheng et al. 2007, Figure 3.2). Both Canada thistle (Cirsium arvense (L.) Scop.) and musk thistle (Carduus nutans L.) usually grow in open area and along roadsides. They compete with desirable forage and grain crops, and are problematic weeds on farms and pastures (Reece and Wilson 1983). The present distributions of these two thistles indicate the specimens were mostly collected in pasture, and are rare in eastern Kentucky, which is dominated by forest (Figure 3.9, 3.10).

Generally, after the initial introduction of an invasive species, the pattern of invasion begins with a lag period of few collections, followed by a period of rapid, exponential expansion. The distribution rate held constant after invasive species completely occupied in a region (Pysek and Richardson 2006; Stadler et al. 1998; Strayer et al. 2006). Exotic
invasive species studied in Quebec (Delisle et al. 2003), France (Chauvel et al. 2006), and North America (Barney 2006) followed this invasion pattern. Our data suggests a lag period with a short, flat portion of the curve at the beginning of the time period for invasive species (Figure 3.6). It appeared that most invasive species in this study were still in their expansion period. The cumulative curves for all species were fitted the “J” shape expansion curve, indicating a potential further invasion of these invasive plants. By combining the invasion curve of species introduced in different time periods, we suggest the early introduction doesn’t necessary contribute to its latter expansion (Figure 3.6).

The overall distribution trend for sixteen invasive species revealed a correspondence between the rapid increase of invasive species and big events in U.S. history. First, during the Great Depression in 1930s, the Agricultural Adjustment Act (AAA) of the New Deal era restricted agricultural production by letting all farms lie fallow. These unmanaged fields provided space for exotic species to invade, which might cause the first explosion around 1930. At the end of World War II in 1945, the United States economy entered a time of unprecedented growth. As a result, urbanization caused an increase in human-disturbed habitat, which might lead to the second explosion of invasion (Addo-Fordjour et al. 2009; Botham et al. 2009). Later, major highways such as I-75 and I-64, completed in 1963 and 1976, respectively, perhaps facilitated the third expansion of existing invasive species and might play an important role during the introduction of some exotic species. Recently, the increasing volume and efficiency of local and global transportation not only continue to introduce new exotic species from abroad, but also serve to spread invasive species already present in a region (Colunga-Garcia et al. 2009).
CONCLUSION

This study on the historical distribution of 16 exotic invasive plants species in Kentucky illustrates the usefulness of herbarium specimens in not only reconstructing the distribution of invasive species but also by identifying potential expansion pathway. It highlights the increasing importance of anthropological activities for non-indigenous species invasion (King et al. 2009; Pejchar and Mooney 2009; Second and Rouhan 2008). Herbaria are invaluable data sources for a wide range of ecological topics. We hope studies such as ours will encourage others to take advantage of the information gathered by botanists and to design novel research utilizing herbarium records.
<table>
<thead>
<tr>
<th>Scientific name</th>
<th>Common name</th>
<th>first documented county</th>
<th>first reported year</th>
<th>current total counties</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Ailanthus altissima</em></td>
<td>tree-of-heaven</td>
<td>Jessamine</td>
<td>1892</td>
<td>58</td>
</tr>
<tr>
<td><em>Paulownia tomentosa</em></td>
<td>princess tree</td>
<td>Fayette</td>
<td>1878</td>
<td>39</td>
</tr>
<tr>
<td><em>Morus alba</em></td>
<td>white mulberry</td>
<td>Fayette</td>
<td>1902</td>
<td>48</td>
</tr>
<tr>
<td><em>Lonicera maackii</em></td>
<td>Amur honeysuckle</td>
<td>Woodford</td>
<td>1960</td>
<td>47</td>
</tr>
<tr>
<td><em>Elaeagnus umbellata</em></td>
<td>autumn Olive</td>
<td>Fayette</td>
<td>1939</td>
<td>32</td>
</tr>
<tr>
<td><em>Rosa multiflora</em></td>
<td>multiflora rose</td>
<td>Mercer</td>
<td>1929</td>
<td>68</td>
</tr>
<tr>
<td><em>Pueraria montana var. lobata</em></td>
<td>kudzu</td>
<td>Fayette</td>
<td>1908</td>
<td>29</td>
</tr>
<tr>
<td><em>Lonicera japonica</em></td>
<td>Japanese honeysuckle</td>
<td>Fayette</td>
<td>1899</td>
<td>100</td>
</tr>
<tr>
<td><em>Euonymus fortunei</em></td>
<td>climbing euonymus</td>
<td>Franklin</td>
<td>1922</td>
<td>47</td>
</tr>
<tr>
<td><em>Polygonum cuspidatum</em></td>
<td>Japanese knotweed</td>
<td>Rowan</td>
<td>1936</td>
<td>76</td>
</tr>
<tr>
<td><em>Microstegium vimineum</em></td>
<td>Japanese stiltgrass</td>
<td>Harlan</td>
<td>1931</td>
<td>71</td>
</tr>
<tr>
<td><em>Cirsium arvense</em></td>
<td>Canada thistle</td>
<td>Madison</td>
<td>1879</td>
<td>42</td>
</tr>
<tr>
<td><em>Carduus nutans</em></td>
<td>musk thistle</td>
<td>Warren</td>
<td>1945</td>
<td>37</td>
</tr>
<tr>
<td><em>Conium maculatum</em></td>
<td>poison-hemlock</td>
<td>Fayette</td>
<td>1902</td>
<td>44</td>
</tr>
<tr>
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Figure 3.1 Historical distribution of Amur honeysuckle (Lonicera maackii (Rupr.) Herder) in Kentucky based on herbaria data from 1960 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Figure 3.2 Historical distribution of kudzu (*Pueraria montana* var. lobata (Willd.) Maesen & S.M. Almeida) in Kentucky based on herbaria data from 1908 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Figure 3.3 Historical distribution of common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) in Kentucky based on herbaria data from 1973 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Figure 3.4 Historical distribution of tree-of-heaven (*Ailanthus altissima* (P. Mill.) Swingle) in Kentucky based on herbaria data from 1892 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Figure 3.5 Historical distribution of Japanese stiltgrass (*Microstegium vimineum* (Trin.) A. Camus) in Kentucky based on herbaria data from 1931 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Figure 3.6 Cumulative number of occupied counties for invasive species introduced from (a) 1878 to 1909, (b) 1910 to 1941 and (c) 1942 to 1973.
Figure 3.7 Historical distribution of princess tree (*Paulownia tomentosa* (Thunb.) Sieb. & Zucc. ex Steud.) in Kentucky based on herbaria data from 1878 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Figure 3.8 Historical distribution of autumn olive (*Elaeagnus umbellata* Thunb.) in Kentucky based on herbaria data from 1939 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Figure 3.9 Historical distribution of Canada thistle (*Cirsium arvense* (L.) Scop.) in Kentucky based on herbaria data from 1879 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Figure 3.10 Historical distribution of musk thistle (*Carduus nutans* L.) in Kentucky based on herbaria data from 1945 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
APPENDICES

Appendix Table 2. A Invasive Exotic Weeds Report Frequency Based on KYWSIP data.

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### Appendix Table 2.A Invasive Exotic Weeds Report Frequency (cont.)

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Appendix Table 3. A Real and virtual Herbaria in and around Kentucky

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<td>Georgetown College</td>
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Appendix Table 3.B Numbers of specimens for sixteen exotic invasive species in herbaria

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Appendix Figure 3.A Locations of herbaria in Kentucky.
Appendix Figure 3.B Sixteen Invasive plants records distribution by the major herbaria in Kentucky.
Appendix Figure 3.C Historical distribution of sericea lespedeza in Kentucky based on herbaria data from 1931 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Appendix Figure 3.D Historical distribution of white mulberry in Kentucky based on herbaria data from 1902 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Appendix Figure 3.E Historical distribution of poison-hemlock in Kentucky based on herbaria data from 1902 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Appendix Figure 3.F Historical distribution of climbing euonymus in Kentucky based on herbaria data from 1922 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Appendix Figure 3.G Historical distribution of Japanese honeysuckle in Kentucky based on herbaria data from 1899 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Appendix Figure 3.H Historical distribution of Japanese knotweed in Kentucky based on herbaria data from 1936 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.
Appendix Figure 3.1 Historical distribution of multiflora rose in Kentucky based on herbaria data from 1929 to 2008. Occupied counties are shaded based on the time period during which the first specimen of that species was recorded. Gray counties are the locations of the earlier plant records.


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EDUCATION
B.S. in Forestry, Beijing Forestry University, 2008  GPA: 3.7
Thesis: Analysis on Spatial Structure of Secondary Betula platyphylla and Populus tremuloides Forest in Wuling Mountain nature reserve in Beijing
Advisor: Dr. Xiaoxian Zheng (Professor in Forestry Management)
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HONORS
College of Ag Richards Scholarship 2009-2010
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Research Assistantship 2008-2010
Outstanding Undergraduate Student Fellowship 2005-2007

WORK EXPERIENCE
(1) Research Assistant, Department of Forestry, University of Kentucky.
2008.10-present
Project: Analysis of Temporal and Spatial Hotspots and Dispersal Corridors of Invasive Species.
  ● Create and manage a digital database of invasive species in Kentucky with Access;
  ● Identify the relationship between land use type and invasive species habitat using SAS;
  ● Identify the hotspots and dispersal corridors of invasive species using ArcGIS

(2) Teaching assistant, FOR599 GIS in Natural Resource, Lexington, KY
2009.8.23-12.15
Project: FOR599 GIS in Natural Resource.
  ● Instruct students to use GPS Unit (Garmin, Trimble) and GIS software such as ArcGIS 9.3.
  ● Grade homework and tests, instruct students to improve their map creation skill.
  ● Tutor students with the feature analysis final projects.

(3) Research Assistant, the Key Laboratory for Silviculture and Conservation of Ministry of Education 2006.10-2008.5
Project: Research on Forest Sustainable Management in Beijing Mountain Area
- Field investigation in Badaling Forest Farm Beijing
- The Execution of stock map based on RS and GIS Technology with Arcview;

Project: Research of Forest Certification
- Translation and collation of Australia Forest Materials

(4) Intern/team leader, Eco-environment Practice in Dongzelinghe Forest Management Station in Xiaoxing’an Mountain of China. 2007.7.2-7.29
- Field investigation, data analysis, forest growing model rectification

(5) Research Assistant, the Laboratory of Wild Plant Protection. 2007.3 -2007.6
Project: Study of Embryo Abortion Mechanism of Ovule in Magnolia
- artificial pollination on Magnolia and isolation with pockets
- blossom and pollination recording
- make Magnolia androecium paraffin section

(6) Team leader, Beijing Forestry Bureau, 2006.7.24-8.1
Project: The Study of the Indigenous Tree Species and a Perfect Tree/Shrub/Grass Combination in Beijing.
- Field investigation, data analysis

(7) Intern, Identification Practice in Forestry in Longmen Forest in the suburbs of Beijing China. 2006.7.10-7.22
Project: Study of causation of Melanconium jugandinum in Longmen Forest
- Field investigation, data analysis and compose thesis

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THESIS AND PUBLICATION

PRESENTATION:


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SKILL:
Experience in collaborating with agencies, organizations, on forestry and natural resource related projects.
Proven knowledge of GIS with an emphasis on ArcGis9 and ERDAS IMAGINE 9.0.
Experience with creating databases to store and manipulate data using Microsoft Access.
Proficient in statistical analyst in SAS, R, and Microsoft Excel.
Proficient knowledge of programming using Visual Basic, and office software like Microsoft Office