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Potential distribution and environmental threat of *Pueraria lobata*

Research Article

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Abstract: *Pueraria lobata* (kudzu) is an invasive weed originating from East Asia. Local infestations have been recently observed in Switzerland and northern Italy; however, the potential for *P. lobata* to spread and to become abundant and damaging in the Alpine countries is not known. The aim of this study was to project the potential distribution of *P. lobata* under current climate in Switzerland, Austria and Slovenia and parts of northern Italy using the ecoclimatic model CLIMEX. In addition, areas at risk were identified where *P. lobata* may occur as a strong and aggressive competitor. This was derived from the plants' distribution and climatic requirements in the south-eastern United States where the heaviest infestations occur. Projections show that 60.84% of the total land area of northern Italy, followed by 47.08% of Slovenia, 21.01% of Austria and only 1.97% of Switzerland are climatically suitable. *P. lobata* may become a troublesome weed due to very favourable climatic conditions only in some parts of northern Italy and Slovenia. In climatically suitable areas, any occurrence of the plant should be carefully observed. In infested and highly climatically suitable areas, there is a need for strategic management to prevent further spread of *P. lobata*.

Keywords: *CLIMEX • Damage niche • Invasive alien plants • Kudzu • Management*

1. Introduction

Pueraria lobata (Willdenow) Ohwi (kudzu) is a leguminous vine native to East Asia with pubescent stems, large trifoliate leaves and a perennial, rhizomatous root system. In the United States, *P. lobata* is of great concern and is known as 'the vine that ate the south' because the plant is an extremely aggressive competitor, forming dense canopies and overtopping surrounding mature tress, houses and roadsides [1-3]. High allocation of resources to extension growth and leaf area, frequent rooting of stems at nodes in contact with soil, high photosynthetic rates and the ability to fix atmospheric N_2 are key traits of *P. lobata*. The plant poses a substantial threat to natural ecosystems, forests and agricultural lands. In the United States, over 3 million ha of land are currently covered by *P. lobata* and the economic damage to managed forests is estimated at 75–380 million € per year [3].

Today, *P. lobata* occurs as an invasive weed in several other countries, including Australia, New Zealand, South Africa and some Central and South American countries [2]. Local infestations of *P. lobata* have been recently found in Switzerland [4] and northern Italy [5,6]. However, in Austria and Slovenia, *P. lobata* has not yet been found [7,8]. How much of the land area of these countries is potentially at risk of an invasion by *P. lobata* is almost unknown. Given the plant's climatic requirements it can be assumed that it will find favourable climatic conditions in the warmer parts of these countries.

The CLIMEX model [9] can be used to project the potential area at risk of an invasion by a particular species based upon its current distribution. This model approach allows exploring the fundamental (potential) niche of a species in its introduced range by assuming that climate alone limits the geographical distribution [10]. CLIMEX is a particularly useful tool at an early stage of an invasion, and is well suited to assess the invasion potential of plant species, as shown for *Senna obtusifolia* (L.) H. S. Irwin & Barneby (sicklepod) [11] and *Cytisus scoparius* (L.)

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Link (broom) [12]. The ability to project suitable areas for high impact weeds is useful in forming the basis of a successful management strategy [11].

However, when management considerations are the primary objective, it is useful to define areas where a species typically occurs as a strong and damaging competitor, the so-called ‘damage niche’ concept as proposed by [13]. Despite its considerable range in the United States, the most severe infestations occur mainly in the piedmont regions of Mississippi, Alabama, and Georgia [14]. It can be assumed that in this geographic range, climatic factors (temperature, precipitation) are a principal determinant for whether *P. lobata* can be abundant and competitive, and therefore damaging. CLIMEX is considered to be a robust methodology for quantifying the damage niche for *P. lobata*.

Information on the establishment and potential distribution of *P. lobata* and its threat to the environment is needed for informed decisions regarding the level and costs of prevention, containment and control of *P. lobata*. Therefore, the objectives of the study were to (1) estimate the potential distribution and relative abundance of *P. lobata* under current climatic conditions and (2) to explore the potential distribution where *P. lobata* may be damaging in Austria, Switzerland, Slovenia and northern Italy.

2. Experimental Procedures

2.1 CLIMEX model and the damage niche

CLIMEX uses an annual growth index (GI) to describe the potential for population growth during favourable climate conditions and four stress indices (cold, dry, wet and hot) to describe the probability of the population surviving unfavourable conditions. CLIMEX also includes a tool for defining the minimum amount of thermal accumulation (number of degree days, PDD) during the growing season that is necessary for population persistence. Thus, CLIMEX excludes areas where the growing season is too short for completion of the life-cycle of a species. The parameter values describing the species’ response to climate were derived from its current geographical distribution and eco-physiological data was used to support the model fitting process [10]. The growth and stress indices were combined into an ecoclimatic index (EI), which indicates the overall climatic suitability of a location for permanent occupation by a species. The EI is scaled from 0 to 100 and implies that naturalization is only possible when the value exceeds zero. Low EI values mean that a location is marginally suitable and large annual fluctuations in numbers of individuals of the species are likely, and indicate that a plant will not take on excessively weedy characteristics, posing little threat to the environment. The EI values were imported to a geographical information system (ArcGIS, Vers. 9.3) to create thematic maps (resolution: 30’ longitude/latitude for Figures 1 and 2 using WGS 1984, and 10’ longitude/latitude for Figure 3 using ETRS89/ETRS-LAEA).

It can be assumed from the distribution in the United States that both temperature and precipitation define the boundaries of the damage niche of *P. lobata* [15]. This species is considered to be troublesome in the eastern and south-eastern United States, particularly in the piedmont regions stretching from Maryland and Virginia in the north, to central Alabama in the south and further on in the lowlands and coastal area of Mississippi and Louisiana (between 30° to 35°N), whereas the heaviest infestations occur in Alabama, Georgia, and Mississippi [14,16]. In this study, the corresponding EI value of this region (Figure 2) is used to define areas where *Pueraria lobata* may occur abundant and damaging to natural ecosystems, forestry and agriculture in Austria, Switzerland, Slovenia and northern Italy (including the regions of the Aosta Valley, Friuli-Venezia Giulia, Liguria, Lombardy, Emilia-Romagna, Trentino-Alto Adige and Veneto).

2.2 Parameter fitting

The parameters for fitting the CLIMEX model were primarily derived from the plants’ distribution using distribution maps of their ranges in Japan [17] and North America [15]. Stress and growth indices were adjusted in an iterative manner until the model closely fitted the distributions in North America and Japan. The parameters are summarized in Table 1 and their values are discussed below. The model’s goodness of fit was verified by comparing the modelled distribution with records of the known distribution in North America (mainly from the periphery), Japan, Europe, New Zealand, South Africa and Australia from the literature [5,18-23], newspaper articles [24,25], herbaria and databases. Databases utilised include the following: USDA Plants Database (http://plants.usda.gov/), Global Invasive Species Database (http://www.issg.org/database/), Global Biodiversity Information Facility (http://www.gbif.org/), ZDSF (http://www.crsf.ch/), Southwest Environmental Information Network (http://swbiodiversity.org/), Invaders Database System (http://invader.dbs.umt.edu/), Flora of the Southeast (http://www.herbarium.unc.edu/seflora/), Texasinvasives.org (http://www.texasinvasives.org/), Invasive Plants Atlas of New England (http://nbii-nin.ciesin.columbia.edu/ipane/) and New York Flora Atlas (http://newyork.plantatlas.usf.edu/).

2.3 Stress indices

2.3.1 Heat stress

The heat stress threshold (TTHS) was set to 35°C with an accumulation rate of 0.005 week^{-1}. This parameter value allows the plant to persist in Austin, Texas (30°16′2″ N, 97°45′50″W), but precludes *P. lobata* from occupying northern and central Mexico and arid and hot locations in Texas, Arizona, New Mexico and California.

2.3.2 Water stress

Pueraria lobata grows well with precipitation of 1000 to 1500 mm per year [2]. In its introduced range, the wettest locations where *P. lobata* has been recorded are in the southern United States (e. g. Homestead, Florida, 25°28′ 6″N, 80°28′ 5″W: 1478 mm; Pensacola, Florida, 30°26′N, 87°12′W: 1633 mm), Australia (e. g. Cairns, Queensland, 16°55′0″S, 145°46′47″E: 2007 mm) and Switzerland (Lugano, 46°0′37″N, 8°57′45″E: 2026 mm). In its native range, for example in China, the plant occurs in the provinces Anhui (Anqing, 30°30′0″N, 117°2′0″E: 1392 mm) and Guangdong (Guangzhou, 23°7′39″N, 113°14′50″E: 1712 mm) [26]. The wet stress threshold (SMWS) was set to 1.8 and the accumulation rate to 0.02 week^{-1} in order to prevent the modelled range from including waterlogged areas and very wet locations e. g. in Indonesia. However, this rate will allow the projected range to include areas exceeding 2000 mm per year.

2.3.3 Cold stress

The northward distribution is limited by cold temperatures [3]. The plant is very frost-sensitive and the aboveground portions die back to the ground in the fall [2]. Recent observations show that *P. lobata* occurs and survives in locations that experience low winter temperatures e. g. in Albany, New York, in 2005 (average annual temperature in January -5.2°C, 42°39′35″N, 73°46′53″W) and Kingsville in southern Ontario, Canada, in 2009 (-4.5°C, 42°2′41″N, 82°36′44″W). A cold stress temperature threshold (TTCS) of 2.5°C and an accumulation rate of - 0.0003 week^{-1} restricted the distribution at the northern limit in the United States, Canada and Japan, where *P. lobata* ranges up to latitude 44°N (e. g. Rumoi, -5.5°C, 43°56′27″ N, 141°38′12″E) [2,17].

2.3.4 Dry stress

Although *P. lobata* is considered to be fairly resistant to drought [2], the western distribution in the United States is limited by low precipitation and prolonged summer droughts. Seedling mortality during the first years of establishment is primarily due to drought stress [15]. According to [15], the distribution is limited to areas in the United States where total annual precipitation is greater than 800 mm, whereas [27] stated that the minimum level of total annual precipitation is 500 mm. Therefore, a relative high value of 0.2 for the dry stress threshold (SMDS) was used with an accumulation rate of -0.095 week^{-1}. These values allow persistence of the species in the eastern part of Texas (Austin, 30°16′2″ N, 97°45′50″W: 854.7 mm; Weslaco, 26°9′33″N, 97°59′15″W, 644.5 mm), but preclude *P. lobata* from the western part of Texas where the annual precipitation is below 550 mm per year.

2.4 Growth indices

2.4.1 Moisture index

Seedling establishment of *P. lobata* is limited by drought and flooding [15,28]. Established populations flourish on many soil types, including sandy, clay, or loamy soils; however, it thrives best on deep, well-drained, loamy soils and the plant languishes in very wet soils and lowlands with a high water table [2,27]. Therefore, the limiting low moisture (SM0) was set to 0.2 and the soil moisture values for optimal growth (SM1 and SM2) were set to 0.5 and 1.0. The limiting high moisture threshold (SM3) was set to 1.8 to account for the presence of *P. lobata* in high rainfall areas in the south-eastern United States and Australia (south-east Queensland, northern New South Wales) and to maintain consistency with the SMWS.

2.4.2 Temperature index

In the south-eastern United States *P. lobata* starts growing in early April (e. g. approximately 13.9°C in Atlanta, Georgia, 33°45′25″N, 84°23′25″W) and continues until checked by cold weather [29]. In the Great Plains area and in the northern Atlantic coastal area in the latitude of New York and the New England States, *P. lobata* survives the winter, but growth starts later and the most rapid growth occurs during the summer months [18]. In its native range in Japan, [30] pointed out that the growing season for *P. lobata* starts in April, with an average monthly temperature of 12.2°C (Nose, Aioi-shi, 34°48′N, 134°28′E). The lower threshold (DV0) was thus set to 12°C. The parameters DV1 and DV2 were set to 25°C and 30°C, respectively, because this is the optimal temperature range for *P. lobata* according to [3]. Notably, these values exhibit the highest EI values in its introduced range in the south-eastern United States, where the plant is abundant and damaging to maintain consistency with the threshold value for heat stress (TTHS), DV3 was set to 35°C.

2.4.3. Thermal accumulation

P. lobata is known to demonstrate viable seed production and seedling recruitment in central Maryland (College Park, 38°59′48″N, 76°55′39″W) and southern

Illinois (La Clede, 38°52′47″N, 88°42′55″W) [21,31]. Far northward in New England, *P. lobata* hardly produces any viable seeds [18,19]. However, sexual reproduction does not appear to be important for persistence and propagation, because the plant reproduces primarily vegetatively [3]. This species grows vigorously and propagates in the area of Kingsville, Ontario (42°2′41″N, 82°36′44″) [24]. Thus, this area was used to fit the threshold value for the minimum heat accumulation parameter (PDD), and according to the Canadian National Climate Data and Information Archive, the value was set to 702°C degree-days.

3. Results

3.1 Model fit and validation

A visual inspection of the projected distribution in North America and Japan showed a very close agreement with the known geographic range of *P. lobata* and this indicates that the CLIMEX model formulation is quite reasonable (Figures 1 & 2). Further independent model validation was possible though comparison between the projected distribution and records of *P. lobata* in the Alpine countries (Figure 3) and Australia, South Africa and New Zealand (data not shown). Almost all recorded locations fall within the projected areas of suitability except some locations in the western part of the United States (Figure 2) and Switzerland (Figure 3). Huachuca City, Arizona (31°38′13″N, 110°20′11″W), is considered to be unsuitable due to dry stress. The annual average precipitation in Huachuca City is 365 mm (data from Fort Huachuca, AZ, 31°33′19″N, 110°20′59″W, Arizona Climate Summaries). Although the species already persisted over five years at this location [20], it was much more reasonable to allow this area to remain unsuitable within the model. A change of the dry stress values predicts a much more extensive range in parts of Arizona and western Texas where *P. lobata* does not occur. The site in Santa Monica, California (34°1′5″N, 118°29′25″W), is excessively dry with 338 mm of annual precipitation (NOAA's National Weather Service). It is very unlikely that this location is within the natural climatic range; anyhow, the plant could persist under irrigation [27]. The San Francisco Bay Area has a Mediterranean climate with dry summers and wet winters (Berkeley, California; 37°52′18″N, 122°16′22″W). The model outlines a cold-dry stress and, particularly in the summer months, precipitation is very low, ranging between 6.35 mm and 25.4 mm (NOAA's National Weather Service). Thus, the climatic suitability of this region should be treated with caution.

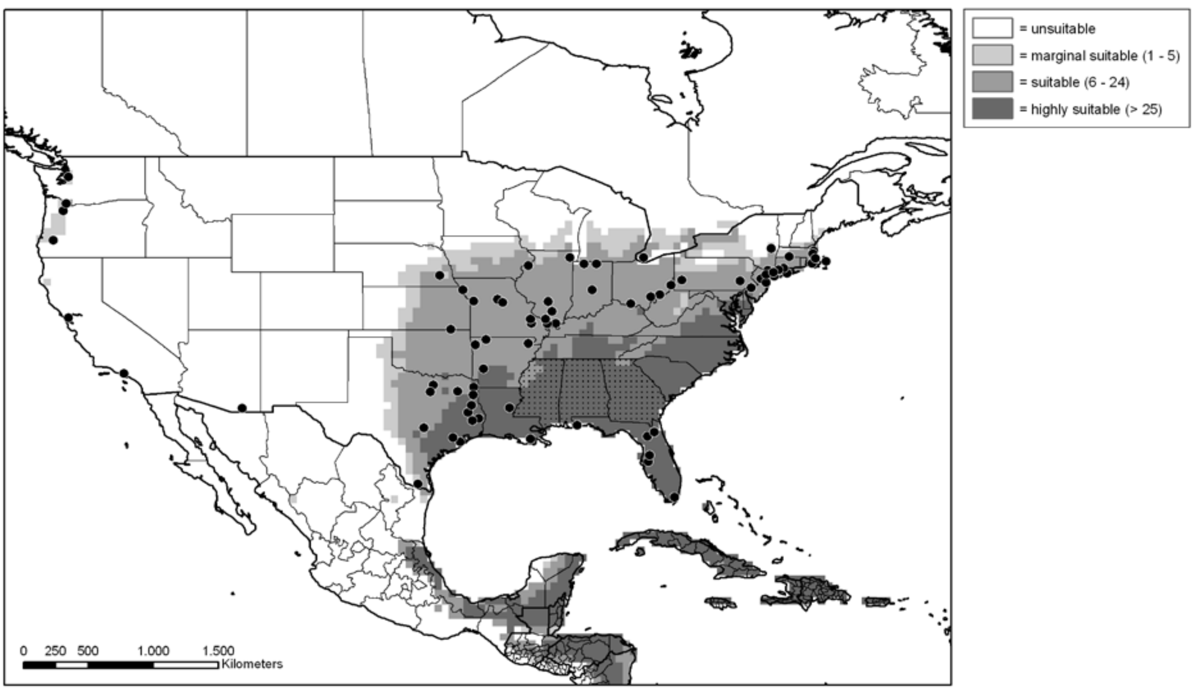

Figure 1. Map of North America showing climatic suitability (ecoclimatic index, EI) for *Pueraria lobata* using CLIMEX and known distribution of the plant mainly from the periphery for goodness of fit. Known occurrences are shown as a point location or at the county level (●). In highly climatically suitable areas (EI > 25), *Pueraria lobata* may occur abundant and damaging. The states of Alabama, Georgia and Mississippi are stippled to indicate the area with the heaviest infestations of *Pueraria lobata*.

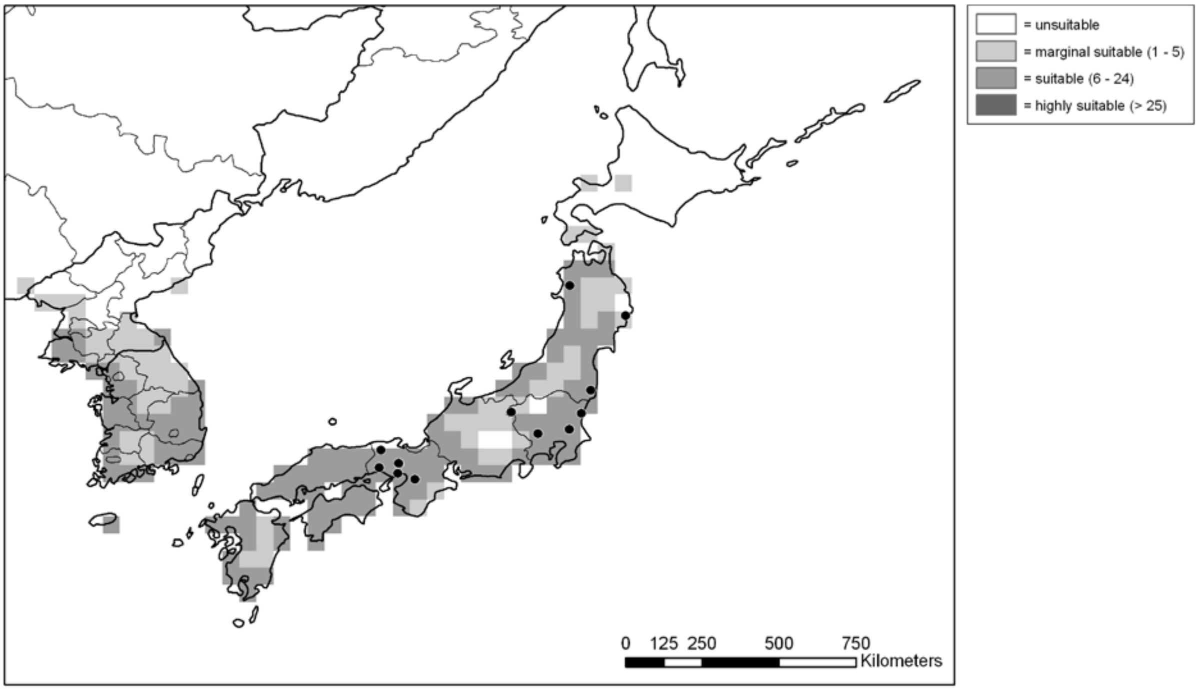

Figure 2. Map of Japan showing climatic suitability (ecoclimatic index, EI) for *Pueraria lobata* using CLIMEX and known distribution of the plant for goodness of fit. Known occurrences are shown as a point location (•).

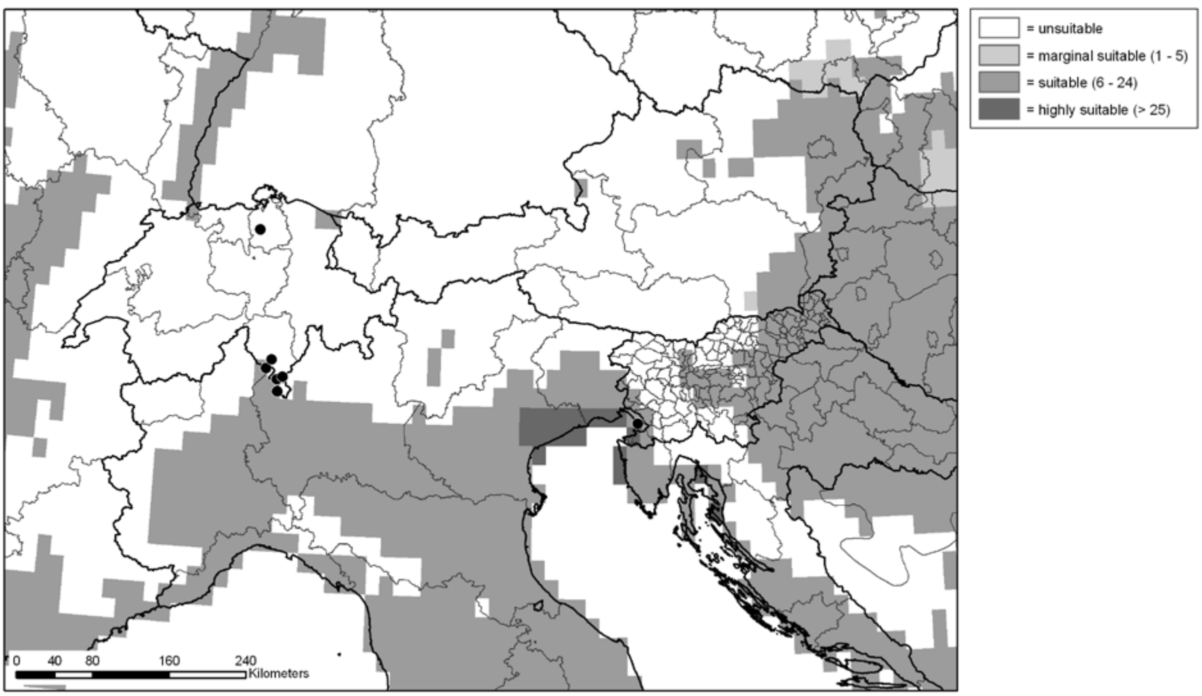

Figure 3. Map of Austria, Switzerland, Slovenia, northern Italy and neighbouring countries showing climatic suitability (ecoclimatic index, EI) for *Pueraria lobata* using CLIMEX and known distribution (•) of the plant for goodness of fit. Known occurrences are shown as a point location (•). In highly climatically suitable areas (EI > 25), *Pueraria lobata* may occur abundant and damaging.

However, this particular specimen found in the San Francisco Bay Area can be traced back to planted or discarded plant material from a Chinese herb wholesaler, and thus is best termed "persistent" following cultivation.

In Zurich, Switzerland (47°22′0″N, 8°33′0″E) it is possible that *P. lobata* could persist, because winter temperatures are moderated by the nearby Lake Zurich. The existence of *P. lobata* at this particular location is most likely due to cultural and microclimatic effects (southern slope) (Buholzer, personal communication). Unfortunately, the CLIMEX model does not project suitable climate for all known records in the area of southern Ticino. Firstly, the climate grids used in this study may poorly represent the climate in this area which is characterised by a multitude of distinct microclimates in which *P. lobata* may persist due to the area's sharp topography and influences of the Lakes Lugano and Maggiore. Secondly, there have been years of milder climatic conditions compared to the long-term average climatic conditions used in this model (1961-1990), which may have favoured *P. lobata* to propagate in this area [32]. This indicates, however, that the projected distribution might be too restricted for the Alpine countries.

3.2 Projected distribution and damage niche under current climate in North America and Japan

The modelled ecoclimatic suitability for *P. lobata* using the parameter values from Table 1 are shown in detailed maps for North America and Japan (Figures 1 & 2). In North America, the geographic range is limited to the eastern half as far westward as Texas and north to the Great Lake States and the Mid-Atlantic States (latitude 45°N). The projected climatic suitability indicates that the plant has almost realized its potential distribution, but could extend its range further northward to the Great Lake states and southern Canada. This is consistent with the observations that *P. lobata* is currently expanding its range to the north. A small part of Washington and Oregon is climatically suitable, yet there are few records of this species in that region. California and the western half of the United States remain unsuitable for *P. lobata*. Figure 1 reflects that in the north severe winter temperatures and in the west insufficient precipitation, together with prolonged drought, limit further spread of *P. lobata*. Areas where the most serious weedy behaviour is reported (*i.e.* Mississippi, Alabama and Georgia) possess an EI value which is greater than 25. Therefore, this value (EI > 25) was used to define the damage niche region of *P. lobata* (Figure 1). This cut-off value coincides well with the plants' distribution and invasiveness (see e.g. in Texas). Large infestations of *P. lobata* occur in the eastern part (Garrison, 31°49′30″N, 94°29′29″W), whereas isolated populations can be found far west (Austin, 30°16′2″ N, 97°45′50″W) according to the information of the databases Texasinvasive.org and GBIF. There is also a good fit with the projected distribution and occurrence

Indices	Parameter	Value
Temperature indices	DV0 = limiting low temperature	12°C
	DV1 = lower optimal temperature	25°C
	DV2 = upper optimal temperature	30°C
	DV3 = limiting high temperature	35°C
	PDD = minimum degree-days above DV0 necessary to complete a generation	702°C
Moisture indices	SM0 = limiting low moisture	0.2*
	SM1 = lower optimal moisture	0.5*
	SM2 = upper optimal moisture	1.0*
	SM3 = limiting high moisture	1.8*
Cold stress	TTCS = cold stress temperature threshold	2.5°C
	THCS = cold stress temperature rate	-0.0003 $week^{-1}$
Heat stress	TTHS = heat stress temperature threshold	34°C
	THHS = heat stress temperature rate	0.005 $week^{-1}$
Dry stress	SMDS = dry stress threshold	0.2*
	HDS = dry stress rate	-0.095 $week^{-1}$
Wet stress	SMWS = wet stress threshold	1.8*
	HWS = wet stress	0.02 $week^{-1}$

Table 1. CLIMEX parameter values used for *Pueraria lobata*. Parameter mnemonics follow [9].

* *dimensionless*

of the plant in Japan (Figure 2). The plant flourishes between 32° to 40°N. The northern limit of distribution in Japan is at latitude 44°N; however, only a very small part of Hokkaido is projected to be suitable. *P. lobata* does not occur as a major pest and the area exhibits an EI value which is lower than 25 (Figure 2).

3.3 Projected distribution and damage niche under current climate in the Alpine countries

The projections of climatic suitability under current climatic conditions in Austria, Switzerland, Slovenia and northern Italy reveal the scope of potential further invasion of *P. lobata* (Figure 3). Only a very small part of Switzerland appears to be climatically suitable, which accounts for 1.97% (813.82 km^2) of the total land area including the southern part of the canton Ticino, a small part of the cantons Basel-Landschaft near the Rhine ditch and St. Gallen near Lake Constance (Figure 2). In Austria, 21% (17640.86 km^2) of the total land area is climatically suitable for *P. lobata*. The potential distribution indicates that the plant can persist in the Vienna basin, the Danube river valley in Lower Austria, Burgenland, and in the municipality of Salzburg as well as in south-eastern Styria with its Illyrian climate. The area at risk of an invasion covers almost 60.84% (73009.47 km^2) of northern Italy except the high altitude areas. The highest EI values can be found in the provinces Friuli-Venezia Giulia, Veneto, Lombardy and the Piedmont. In Slovenia, approximately 47% (9540.41 km^2) of the land area can be invaded by *P. lobata*. Parts of Upper Carnolia and Inner Carnolia are projected to be climatically unsuitable. *P. lobata* can potentially invade large areas of other Central European countries like Hungary and Slovakia (Figure 3).

Table 2 shows that in Austria and Switzerland the EI values are lower than 25 in all climatically suitable areas. In northern Italy in the regions of Friuli-Venezia Giulia and Veneto and in south-western Slovenia on the Gulf of Piran only 1.12% and 0.56% of the land area, respectively, is projected to have an EI value greater than 25, and thus be optimal for the plant.

4. Discussion

In the Alpine countries, the projected distribution under current climate is far greater than currently occupied. In Austria, the plants' potential distribution is restricted to the warmer and lower parts in the east, and in Switzerland to Lake Constance and the Upper-Rhine valley, respectively. In high altitude areas, the CLIMEX model projects that the climate is unsuitable mainly due to a combination of cold stress and lack of thermal accumulation. The distribution and spread of *P. lobata* is determined by the extent of above-ground dieback of overwintering stems and the minimum winter temperatures which kill the crown and root system of the plant. In Japan, *P. lobata* occurs up to 1200 m above sea level and scattered populations can be found up to the northern Island of Hokkaido, south of 44°N [17], indicating that the plant is very well-adapted to low temperatures. However, it can be assumed from the predicted performance that it is unlikely that *P. lobata* could significantly expand its population due to slower growth rates and perennial increase in patch size in the climatically suitable areas of Austria and the northern part of Switzerland. This is comparable to the situation in the northern regions of the United States [15].

The species may become more of a problem in the region south of the main chain of the Alps. Higher minimum temperatures, a decrease in the number of frost days and higher precipitation levels favour establishment and spread of *P. lobata*. The surrounding areas of the naturalized populations in the canton Ticino in Switzerland and bordering Italian regions have

	Land area suitable		Land area within the damage niche	
	Land area (km^2)	% of total land area	Land area (km^2)	% of total land area
Austria	17640.86	21.01	0.0	0.0
Switzerland	813.82	1.97	0.0	0.0
Italy*	73009.47	60.84	1341.23	1.12
Slovenia	9540.41	47.08	113.69	0.56

Table 2. Land area projected to be climatically suitable (ecoclimatic index, EI > 1) for *Pueraria lobata* and land area where the plant may occur abundant and damaging (EI > 25, damage niche) in the Alpine countries using CLIMEX expressed as an area (km^2) and a percentage of the total land area.

* *including the regions Aosta Valley, Friuli-Venezia Giulia, Liguria, Lombardy, Emilia-Romagna, Trentino-Alto Adige and Veneto*

proven to be an ideal environment for the proliferation of many introduced species from warmer parts of the world (e. g. [33]). The EI values for this region (EI < 25) indicate that the climate is not optimal for *P. lobata* to take on excessively weedy characteristics, though this species is recorded as a localized problem, invading open habitats and forest edges around Lake Maggiore and Lake Lugano (Follak, unpublished data). In this respect, [18] noticed that isolated populations in areas of Massachusetts and Connecticut with a similar EI value produce 10 to 15 m of annual stem growth although the stems are killed back to the overwintering crown each year.

As *P. lobata* is occasionally cultivated as an ornamental in private gardens, such plantings could form foci for naturalisation and invasion, particularly in northern Italy, where the EI of large areas was projected to be suitable for this species. In parts of Friuli-Venezia Giulia and Veneto, potential exists for *P. lobata* to achieve the same degree of invasiveness (EI > 25) as in the south-eastern United States. In such climatically optimal areas, stem elongation up to 30 m is possible in a single growing season [34]. Of particular concern are protected natural areas, forest regeneration or recolonization areas as well as permanent crops where *P. lobata* may encroach from adjacent infestations [1,14]. The mild climate in this area may also result in *P. lobata* producing viable seeds and vigorous seedlings. It is reported that the plant is capable of germinating in a variety of climatic and edaphic conditions [28].

It is important to stress that the results of the study demonstrate how the distribution and impact of *P. lobata* could potentially develop under current climatic conditions. The CLIMEX model assumes that climate is the primary determinant of the potential distribution. However, there are other abiotic and biotic factors that influence the distribution and impact of an invasive species, including disturbance patterns, herbivory, provenance and land use [10]. For example, it has been shown that *P. lobata* populations from China (Anhui Province) and the United States (North Carolina) tend to vary in their growth rate and biomass production [35], which may influence its growth habit and competiveness. However, the government-aided planting of *P. lobata* during the first half of the 20th century and the social and agricultural changes leaving *P. lobata* plantings uncontrolled have also contributed to its spread and invasiveness throughout the south-eastern United States [3]. Without deliberate cultivation and unintentional dispersal by humans (e. g. movement of vegetative tissue by construction work, disposal of garden waste), *P. lobata* is believed to spread slowly [21]. Notably, climate change may alter the distribution of *P. lobata* as demonstrated by [16] for the eastern United States.

P. lobata will most likely not become a widespread and aggressive competitor in the Alpine countries due to climatic constraints, but there is certainly a need for a strategy for prevention, containment and control of this species. The main risk arises from gardeners cultivating *P. lobata* as an ornamental in climatically and otherwise suitable areas who leave *P. lobata* plantings to uncontrolled growth and allowing plants to spread into edge habitats and forest areas. Thus, it is important to increase public awareness of the risk posed by this plant and to declare the plant as unsuitable for ornamental purposes. In already infested and highly climatically suitable areas, major components of a management strategy include the containment of naturalized populations to their local distribution and surveillance of the surrounding area to detect the appearance of nascent foci. Various control and eradication programs have been explored to manage the spread of *P. lobata* in the United States (e. g. [36]), but due to its extensive rooting, repeated physical removal or herbicide application over several years are required to fully control this plant [3].

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Appendix 1. Distribution data (known occurrences) of *Pueraria lobata* for North America, Japan and Central Europe shown in Figures 1, 2 and 3.

Location	Reference
North America – USA (location, county, state)	
Adams County, OH	USDA
Albany, Albany County, NY	NYFA, Lamere (2006)
Allegheny County, PA	USDA, Rhoads & Klein (1993)
Athens, Athens County, OH	Hickman (2009)
Austin, Travis County, TX	Texasinvasive.org (#395*)
Belmont County, OH	USDA
Berkeley, Alameda County, CL	GBIF
Berks County, PA	Rhoads & Klein (1993)
Brandon, Hillsborough County, FL	FLAS (#191168)
Canby, Clackamas County, OR	Invaders database system
Carroll County, AR	USDA
Cass County, TX	USDA
Catahoula Parish, LA	SEINet (#14372)
Clark County, WA	Invaders database system
Clay County, FL	FLAS (#197029)
Dartmouth, Bristol County, MA	[18]
Denton, Denton County, TX	Texasinvasives.org (#9917)
Diana, Upshur County, TX	Texasinvasives.org (#11128)
Elkhart County, IN	USDA, DNR
Evanston, Cook County, IL	[21], McElroy (2005)
Fairfield, Fairfield County, CT	IPANE (#21468), NYFA (#40708)
Fayette County, IL	[21]
Fayette, Howard County, MO	GBIF
Fish and Wildlife area, Union County, IL	[21]
Fort Worth, Tarrant County, TX	Texasinvasives.org (#3638)
Gainesville, Alachua County, FL	FLAS (#110660, #108608)
Garrison, Nacogdoches County, TX	Texasinvasives.org (#8386)
Greene County, AR	USDA
Greenwich, Fairfield County, CT	IPANE (#22585, #22804)
Homestead, Miami-Dade County, FL	FLAS (#137749)
Howard County, MO	USDA, MDC
Huachuca City, Cochise County, AZ	[20], SEInet (#267690)
Hull, Plymouth County, MA	[18]
Jackson County, IL	[21]
Jackson County, MO	USDA, MDC
Jasper, Jasper County, TX	Texasinvasives.org (#11031, #10903, #11004)
Jefferson County, IL	[21]
Kingston, Plymouth County, MA	[18], IPANE (#1224, #21587)
LaFourche Parish, LA	GBIF
LaPorte County, IN	USDA, DNR
Lincoln, Lancaster County, NE	[29]
Liverpool, Brazoria County, TX	Texasinvasives.org (#8349)
Lufkin, Angelina County, TX	Texasinvasives.org (#12631)
Madison County, MO	USDA, MDC
Manchester, Essex County, MA	IPANE (field record)
Marion County, IN	USDA, DNR
Marshall, Harrison County, TX	Texasinvasives.org (#11615)
Middlesex County, NJ	[19]
Monmouth County, NJ	[19]
Montgomery County, AR	USDA

* *accession number (databases and herbaria)*

continued **Appendix 1.** Distribution data (known occurrences) of *Pueraria lobata* for North America, Japan and Central Europe shown in Figures 1, 2 and 3.

Location	Reference
Montgomery County, KS	KSU, USDA
Nassau County, NY	[19], NYFA
New Haven, New Haven County, CT	[18], IPANE (#375, #380)
New York City, NY	[19], Lamont (2002), NYFA
Orleans, Barnstable County, MA	[18]
Pasco County, FL	USDA, PlantAtlas.org
Passaic County, NJ	[19]
Pensacola, Escambia County, FL	USDA, GBIF
Peoria, Peoria County, IL	[21], McElroy (2005)
Philadelphia, Philadelphia County, PA	[3], Miller & Edwards (1983)
Richmond, Ford Bent County, TX	Texasinvasives.org (#7256)
Rock Island, Rock Island County, IL	[21]
Rockland County, NY	[19], NYFA
Roseburg, Douglas County, OR	Invaders database system
Santa Monica, Los Angels County, CL	GBIF
Scarsdale, Westchester County, NY	[19]
Seattle, King County, WA	GBIF
Shawnee National Forest, Harrisburg, IL	[21]
Springfield, Hampden County, MA	[18]
St. Francois County, MO	USDA, MDC
Suffolk County, NY	[19], NYFA
Troy, Doniphan County, KS	GBIF
Washington County, AR	USDA
Washington County, OH	USDA
Weslaco, Hidalgo County, TX	[22]
Woodville, Tyler County, TX	Texasinvasives.org (#10950, #1131, #1424)
North America – Canada (location, county, state)	
Kingsville, Essex County, Ontario	McEwen (2009), [25]
Japan (prefecture, location)	
Hyōgo, Himeji	GBIF
Hyōgo, Matsuho	GBIF
Hyōgo, Chūō-ku	GBIF
Hyōgo, Kitakatsuragi	GBIF
Hyōgo, Yabu	GBIF
Gunma, Tsumagoi	GBIF
Saitama, Tonosu-yama	GBIF
Fukushima, Iwaki	GBIF
Ibaraki, Ami-machi	GBIF
Ibaraki, Tōkai	GBIF
Iwate, Kamaishi	GBIF
Akita, Fujisato	GBIF
Central Europe (location)	
Zürich	ZDSF
Tronzano	EPPO (2007), ZDSF
Locarno	ZDSF
Magliaso	EPPO (2007), ZDSF
Triest	[5]
Viggiù	EPPO RS 2008/148
Lugano	ZDSF, EPPO (2007)

* *accession number (databases and herbaria)*

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Databases and herbaria

PlantAtlas.org - Atlas of Florida Vascular Plants (http://www.plantatlas.usf.edu/)

DNR - Department of Natural Resources, Indiana (http://www.in.gov/dnr/entomolo/5908.htm)

FLAS - University of Florida Herbarium (http://www.flmnh.ufl.edu/herbarium/)

GBIF - Global Biodiversity Information Facility (http://www.gbif.org/)

Invaders Database System (http://invader.dbs.umt.edu/)

IPANE - Invasive Plants Atlas of New England (http://nbii-nin.ciesin.columbia.edu/ipane/)

KSU - Kansas State University Online Herbarium (http://www.konza.ksu.edu/herbmap/)

NYFA - New York Flora Atlas (http://newyork.plantatlas.usf.edu/)

SEINet - Southwest Environmental Information Network (http://swbiodiversity.org/)

Texasinvasives.org (http://www.texasinvasives.org/)

USDA - United State Department of Agriculture Plants Database (http://plants.usda.gov/)

ZDSF - Zentrum des Datenverbundnetzes der Schweizer Flora (http://www.crsf.ch/)