Spread Dynamics of *Abutilon theophrasti* in Central Europe

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Abstract

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The spread pattern of *Abutilon theophrasti* (velvetleaf) in Austria, the Czech Republic, and Slovakia was analysed based on an exhaustive distribution data set (389 records). Cumulative number of all records showed a continuous increase since its introduction in the 19th century and > 1970 its spread gained momentum with an exponential increase > 2000. In fields, the species remained rare until 2000. Since then, *A. theophrasti* has invaded fields much more frequently (78% of all records in fields > 2000) and it was mainly found in sugar beet and maize. Approximately a total of 188 000 ha of the agricultural area are currently at risk of being invaded. Given the on-going spread into fields, the results provide evidence that *A. theophrasti* may cause serious impacts. Control measures should focus on the prevention of spreading seeds and the establishment of new foci.

Keywords: alien plant species; distribution; invasion history; velvetleaf

Abutilon theophrasti (velvetleaf) has become a problem weed in many countries in Europe (Weber & Gut 2005). This species is highly competitive while it is primarily competing for light with the crop plant (Warwick & Black 1988; Lindquist *et al.* 1998). If *A. theophrasti* and the crop emerge simultaneously, it can surpass crop growth, which ultimately results in reduced yield due to interference with crop light interception (Sattin *et al.* 1992). However, yield losses vary largely depending on the crop type infested, weed density, and environmental conditions (Schweizer & Bridge 1982; McDonald *et al.* 2004). Moreover, its importance has increased over time, partly because it is relatively tolerant to many herbicides (Sattin *et al.* 1992).

In southern and south-eastern European countries, *A. theophrasti* is widely established in agricultural areas. For example, in northern Italy, the species was known for centuries, however the first reported infestation of fields was in 1969 and since then the species has become a troublesome weed (Sattin *et al.* 1992). *Abutilon theophrasti* is also frequently found in fields in Hungary (Novak *et al.* 2009) and Serbia (Vrbničanin *et al.* 2008). Recent studies indicated that in Austria, the Czech Republic, and Slovakia and in other countries of Central Europe *A. theophrasti* can be increasingly found (Meinlschmid 2006; Medvecká *et al.* 2012; Pyšek *et al.* 2012a; Follak 2013). Hence, further spread will create serious agricultural problems in Central Europe.

Studying the spread of alien plant species in the past provides insights into spatio-temporal spread pattern and may help to identify management strategies and to assess the potential of further expansion and distribution limits (Lavoie *et al.* 2007; Follak *et al.* 2013). The present study sets out to analyse the spread dynamics of *A. theophrasti* in Austria, the Czech Republic, and Slovakia based on an exhaustive distribution data set from a wide range of sources. All these countries have a strong floristic tradition, so that the information necessary for retrospective analysis exists (Essl *et al.* 2009; Pyšek *et al.* 2012b). In this study, the following three questions were addressed: (1) What is the spatio-temporal spread pattern of *A. theophrasti*? (2) How much of the agricultural area and which crops are at risk of being invaded? (3) What are the implications for impact and management?

MATERIAL AND METHODS

Study species. *Abutilon theophrasti* Medik. (*Malvaceae*) is native to China and it was originally introduced in many parts of the world as a potential fibre crop and later it has been accidently imported as a seed contaminant (Jäger 1991; Holt & Boose 2000). It is an annual broadleaf C_3 species with an erect habit and large, alternate, heart-shaped, and heliotropic leaves and yellow-orange flowers and it is characterised by a rapid growth and high photosynthetic rates. It has typical seed pods containing up to 40 large, hard black seeds (Warwick & Black 1988). This species produces many seeds (up to 8000 seeds per plant), which can remain viable for decades in the soil contributing to its long-term success (Spencer 1984).

Data collection and analysis. All available records of *A. theophrasti* in Austria, the Czech Republic, and Slovakia up to 2013 have been collected from a wide range of sources (Supplementary Online Material). Only sources were included in the study, which ensured reliability and accuracy of the records (e.g. refereed scientific journals, non-refereed floristic journals, records from taxonomic specialists, official collections; criteria used were according to FAO 2006). Records were cross-checked to avoid double entries of identical records in different data sources. In total, 389 unique records of *A. theophrasti* were collated. All records have been assigned to a grid cell (5 × 3 geographic minutes, ~33 km^2) of the Floristic Mapping Project of Central Europe (FMCE) (Niklfeld 1998). The year of the records was extracted from the original source. Data on colonised habitat types have been collated from each record containing site characteristic information and were assigned to the following two categories: fields (collected within a crop field, field margin) and outside fields (collected on ruderal places like dump sites, railway stations, harbour or in gardens). A total of 357 records (92% of all records) contained site information. Moreover, for each record in fields the invaded crop and the size of the population (records > 2000; classified into three categories: < 10, 10–100, > 100 individuals) were documented by using information in the original data source.

The total distribution in fields (> 2000) was mapped for three time periods (< 1970, 1971–1990, and 1991–2013) to show the spatio-temporal pattern of spread. The invasion rate of *A. theophrasti* into different habitats (i.e. fields vs. outside fields) was analysed by calculating the cumulative number of records plotted against time according to Pyšek and Prach (1993). Regression models were then fitted to the cumulative number of records and the slope *b* was used as a measure of the invasion rate (Mandák *et al*. 2004). The data was analysed using a General Linear Model with species as a factor and year as a covariate. Statistical analyses were performed using IBM® SPSS® software, Vers. 20. Grid cells (representing an area of ~33 km^2) with records in fields were separated into two time periods (i.e. 1990–1999 and 2000–2013) in order to show the change in overall agricultural area at risk of being invaded in the two recent decades. To calculate the agricultural area in each grid cell, the CORINE land cover dataset 2006 (http://www.eea.europa.eu/data-and-maps/) was used for Austria, the Czech Republic, and Slovakia. According to the CORINE land cover classes, agricultural areas include arable land, permanent crops, pastures, and heterogeneous agricultural areas (http://etc-lusi.eionet.europa.eu/CLC2000/classes).

RESULTS

First data on the occurrence of the species .In the study area, *A. theophrasti* was first found in the middle of the 19th century (Figure 1A). In Slovakia, *A. theophrasti* was first mentioned already in 1865 in Kostolné ("inter segetes circa Kosztolan"; Knapp 1865). Further early records were from south-western and western Slovakia in the area of Štúrovo (1868) and from Dvorníky (1866) (Jehlík 1998). In Austria, the first record of *A. theophrasti* is a herbarium specimen

Table 1. Change of agricultural area at risk of being invaded by *Abutilon theophrasti* in the study area (Austria, Czech Republic, Slovakia) over two time periods based on the grid cells with records in fields and the CORINE land cover dataset 2006 (category: agricultural areas)

	1990–1999		2000–2013	
	agricultural area (ha)	total agricultural area (%)	agricultural area (ha)	total agricultural area (%)
Austria	7.3532	0.27	87.4034	3.19
Czech Republic	2.4681	0.05	43.2888	0.95
Slovakia	17.0344	0.70	57.1542	2.35
Total	26.8557	0.28	187.8464	1.93

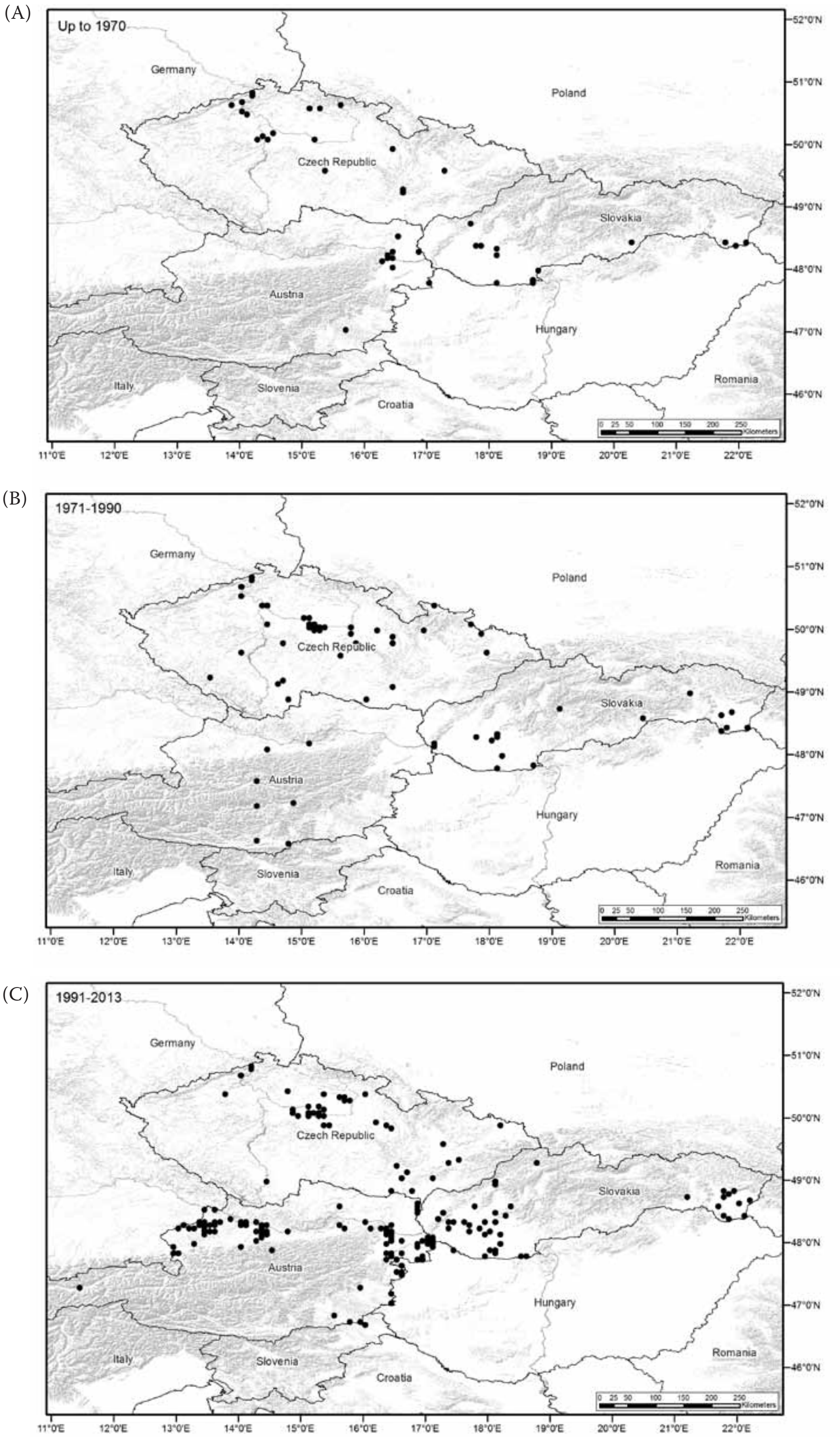

Figure 1. Distribution maps of *Abutilon theophrasti* in the study area (Austria, Czech Republic, Slovakia) for the time periods (A) up to 1970, (B) 1971–1990, and (C) 1991–2013 based on the grid (5 × 3 geographic minutes, ~33 km^2) of the Floristic Mapping Project of Central Europe

from 1873 ("Austria inferior, in hortis spontanea"; deposited at the Museum of Natural History Vienna), whereas in the Czech Republic the species was firstly described in 1894 in Brno ("Kartause Königsfeld" = Kartouza Královo Pole; deposited at the Museum of Natural History Vienna). In Slovakia, apart from the early record (1865) in fields, *A. theophrasti* was described in fields in 1930 in Ladmovce and in the 1980s in the area of Komárno and Štúrovo (Jehlík 1998). In Austria and the Czech Republic, the species was first

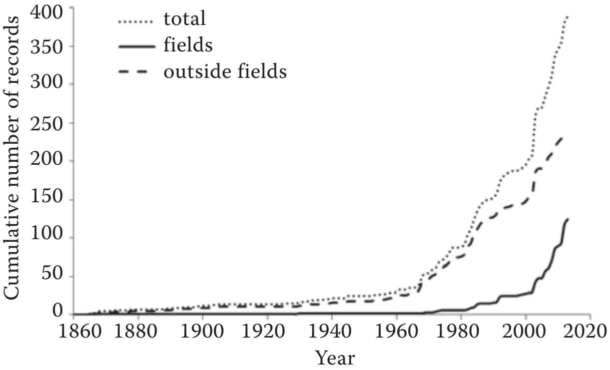

Figure 2. Cumulative number of all records and records in fields and outside fields of *Abutilon theophrasti* in the study area (Austria, Czech Republic, and Slovakia)

mentioned in fields in 1973 in Bleiburg and 1972 in Veltruby, respectively (Melzer 1974; Jehlík 1998).

Spatio-temporal spread pattern. In its initial phase of the invasion process, the distribution of *A. theophrasti* was limited to several isolated locations in the study area (Figure 1A). The visual inspection of the plot of the cumulative number of all records indicates that *A. theophrasti* had spread slowly across the study area until 1970 (Figure 1B). Then its spread gained momentum and more than 60% of all records (238) were collected in the period from 1990 to 2013 (Figure 2). The cumulative number of records outside fields showed a quite similar pattern than that of the total number with a considerable increase > 1970. *Abutilon theophrasti* was frequently found outside fields on urban waste places (e.g. on sites where waste from factories processing wool, soybeans, sugar-beet or oil plants has been dumped), in ruderal habitats associated with transport infrastructure (railway stations, silos, harbour), gardens, and along riverbanks.

The cumulative number of records in fields had increased slowly until 2000 (Figure 2). Since then, *A. theophrasti* has invaded fields much more frequently (78% of all records in fields have been collected > 2000). *Abutilon theophrasti* was more often found in fields in Austria (49% of all records in fields) followed by Slovakia (27%), and the Czech Republic (24%). The slopes (b) from the regression of the cumulative number of records in fields and outside fields for the whole period (1865–2013) were tested to compare their rate of spread. The model explained 90% of variance (F = 903.79; df = 3; P < 0.001).The slopes were not significantly different (F = 1.696; df = 1; P > 0.05) with b = 0.013 for populations outside fields and b = 0.012 for populations in fields.

Agricultural area and crops at risk of being invaded. Today, larger populations of *A. theophrasti* in fields can be found in the Danubian Lowland, in the Košice Region (Slovakia), Central Bohemia, South Moravia (Czech Republic), and in Burgenland, Upper Austria and in the Vienna Basin (Austria) (Figure 3). The agricultural area at risk of being invaded by *A. theophrasti* is presumed to be low, but increased from 26 855 ha (0.3% of the total agricultural area) to 187 846 ha (1.93%) in the study area (Table 2). The greatest increase in the agricultural area at risk between the two periods was observed in the Czech Republic (17.5-fold), followed by Austria (11-fold) and Slovakia (3.5-fold). *Abutilon theophrasti* occurred in spring-sown crops like sugar beet (39% of all records in fields), maize (18%), sunflower (10%), followed by soybean (4%) and other crops like potatoes, oil-pumpkin, and vegetables (5%) (24% could not be assigned to a specific crop). Most of the records > 2000 (n = 98) in fields were small populations (39%; < 10 individuals), followed by medium (29%; 10–100) and large (8%; > 100) populations. For

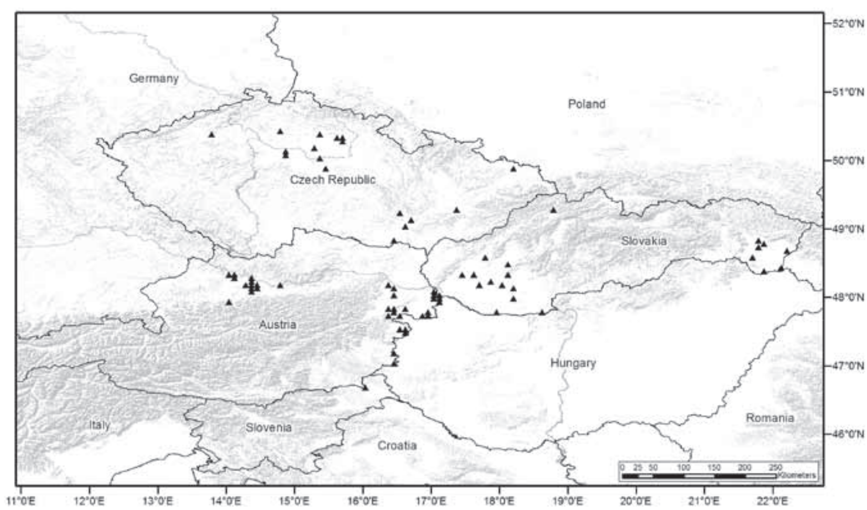

Figure 3. Current distribution (records > 2000) of *Abutilon theophrasti* in fields (n = 98) in the study area (Austria, Czech Republic, Slovakia) based on the grid (5 × 3 geographic minutes, ~33 km^2) of the Floristic Mapping Project of Central Europe

24% of these records no information on the population size was available (Figure 3).

DISCUSSION

Introduction and spread pattern. The invasion process of *A. theophrasti* shows three distinct stages. Early records of *A. theophrasti* were spontaneous and short-lived casual occurrences in gardens and in ruderal habitats (waste places) in larger cities (e.g. Vienna, Prague) and scattered over the study area (Figure 1A). These were probably escapes from former cultivations (though inside the garden) as the species has been cultivated as a medicinal, fibre or ornamental plant (Jäger 1991). Small populations were found in southern Slovakia along the border, which may have been introduced with grain and other goods imported from Hungary (Jehlík & Hejný 1974). The invasion of *A. theophrasti* increased considerably in the Czech Republic and Slovakia in the period 1971–1990 (Figures 1B and 2) and was mediated by anthropogenic long-distance dispersal via contaminated grain and oil-seeds (e.g. cereals, soybean) from North America and from the former Soviet Union (Jehlík & Dostálek 2008; Pyšek *et al.* 2011). Hence, the species was frequently found in larger cities along the rivers Elbe and in cities with railway stations and re-loading facilities (Figure 1B) (Jehlík 1998). Once established in a new area, these populations served as a source for further short- and long-distance dispersal in random directions, e.g. in Central Bohemia (Kolín district) or in the Košice region (Trebišov district) (Figures 1A and 1B). In Austria, however, the species spread was rare as records in this period were rather low and they were found almost exclusively in ruderal habitats (i.e. urban waste places, sand pits) reflecting other pathways, e.g. contaminated bird seed or garden escapes. After 1991 until present, in the Czech Republic and Slovakia, short-distance dispersal became dominant indicated by the on-going occupation of adjacent grid cells (Figures 1B and 1C) while new introductions as a contaminant in grain and oil-seeds from abroad and eastern countries decelerated (Pyšek *et al.* 2011). *Abutilon theophrasti* has been increasingly observed in Austria (Figure 1C) indicating that introduction, establishment of founder populations and subsequent spread of the species was delayed compared to the Czech Republic and Slovakia.

There are currently four distinct invasion hotspots in the study area (Figure 1C): (1) Central Bohemia (Czech Republic), (2) Eastern Slovak Lowland (SE Slovakia), (3) Danubian Lowland (SW Slovakia,), Vienna Basin, northern Burgenland (E Austria), South Moravia (Czech Republic), and (4) Upper Austria (W Austria). The distribution pattern of *A. theophrasti* accords well with the fact that the intensity of plant introductions depends largely on dynamics of historical, social, and economic events (Pyšek *et al.* 2011). Moreover, our observations suggest that the invasion of *A. theophrasti* showed no clear front in the study area but occurred through means of scattered satellite populations from original centres of introduction. Such a spread pattern has been demonstrated already for the invasive weed *Ambrosia artemisiifolia* L. (common ragweed) in Central Europe (Essl *et al.* 2009).

Agricultural area and crops at risk of being invaded. *Abutilon theophrasti* has become a troublesome weed in agriculture particularly in parts of the lowlands of the study area (Týr & Vereš 2010; Mikulka 2011; Follak 2013). It started to invade fields noticeably in the 1970s and the agricultural area at risk has increased over the past two decades due to its spread within and across grid cells. It seems likely that the expansion of *A. theophrasti* in agriculture was fostered by unintentional human-mediated dispersal. The most important dispersal pathways are contaminated catch crop seeds, supplementary fodder seeds for wild animals, organic fertilizers (Meinlschmid 2006; Eliáš 2011), and seeds attached to tillage and harvest equipment (Warwick & Black 1988). In neighbouring countries, in Hungary, *A. theophrasti* began to invade fields also in the 1970s and its spread has continued until today (Novak *et al.* 2009), while in Germany, the invasion of *A. theophrasti* in fields appeared to have taken place much later (> 2000; Meinlschmid 2006).

Likewise in other countries (Meinlschmid 2006; Vrbničanin *et al*. 2008; Novak *et al*. 2009), the results show that *A. theophrasti* was frequently found in spring-sown crops like sugar beet and maize in the study area. Experimental interference studies under Central European conditions show that the impact of *A. theophrasti* on these crops can be significant (Kovács *et al.* 2006; Dávid *et al.* 2007). Most of the recently observed populations of *A. theophrasti* in fields were only of small to medium size. It can be assumed that the species is already present in many locations in the study area, but most populations are too small to cause significant economic damage (i.e. they were below the economic threshold, e.g. Schweizer & Bridge 1982). However, the return of seeds from even sparse populations could have long-term consequences for weed management as seeds of *A. theophrasti* can remain viable in soil for decades (Spencer 1984) and seeds produced by a low number of individuals of *A. theophrasti* will result in increasing seedling populations in subsequent years well above the economic threshold as demonstrated by Cardina and Norquay (1997).

Potential future distribution and controlling its further spread. The results indicate that *A. theophrasti* will expand its range further as the saturation phase of the invasion has not been reached as shown by the increasing number of records and grid cells infested (Figures 1C and 2). The current distribution pattern shows that the species is confined to warmer regions in the study area (e.g. lowlands in Austria and Slovakia). However, *A. theophrasti* can already be found in cooler regions (e.g. Little Carpathians of Slovakia, Figures 1C and 3). Similarly, in the course of its northward spread in North America, *A. theophrasti* has already colonised areas with cooler climates than in its native range (Clements & DiTommaso 2012). A more northward and latitudinal expansion of *A. theophrasti* in fields can be expected in the study area, as the species has a remarkable ability to adapt to cooler climates (Warwick & Black 1988; Westerman *et al*. 2012).

Control options should include the prevention of the introduction of *A. theophrasti* into previous uninfested fields and environments by avoiding spreading seeds via contaminated soil and harvesting. In fields, management should target on the surveillance of incipient infestations and subsequent uprooting of small populations before seed set. Already infested fields with larger populations could be managed thoroughly with herbicides. The effectiveness of herbicides in different crops has already been tested (e.g. Meinlschmid *et al*. 2004; Jursík *et al.* 2011). In sugar beet, however, control requires a sequence of herbicide applications together with mechanical weed control (Jursík *et al.* 2011). If management options mentioned above are consequently implemented there may be a substantial chance to limit further spread in fields.

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