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Spread dynamics and agricultural impact of *Sorghum halepense*, an emerging invasive species in Central Europe

S FOLLAK* & F ESSL†

*Austrian Agency of Health and Food Safety, Vienna, Austria, and †Federal Environment Agency, Vienna, Austria

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Summary

Sorghum halepense is a serious weed and reservoir for pathogens of crops worldwide that has recently spread in Austria. On the basis of an exhaustive distribution data set (302 records), we analysed the spread dynamics and agricultural impact. The first record of *S. halepense* was recorded in 1871, but the species remained rare until 1970. After a moderate increase in records until 1990, it has recently expanded strongly (>70% of all records have been collected since 1990), in particular, in the lowlands of eastern and southern Austria. Invasion into fields was first documented in the 1970s, but again, since 1990, *S. halepense* has spread strongly and fields now account for 32% of all records. In southern Austria, we found that *S. halepense* invasion already puts approximately 41% of grain maize fields and 40% of oil-pumpkin fields at risk of yield losses. In cooler regions within Austria, *S. halepense* is still rarely recorded in fields. *Sorghum halepense* serves as a reservoir for the maize dwarf mosaic virus, as it was found in 38% of 21 samples collected in southern Austria. Invasion of *S. halepense* in fields was most likely assisted by frequent secondary dispersal and intensive maize and oil-pumpkin cultivation. Given the fast and on-going spread in fields, which is likely to continue under climate warming, our results provide evidence that *S. halepense* will cause serious impacts for agriculture in Austria and probably in other countries of Central Europe.

Keywords: agriculture, alien species, Johnsongrass, maize dwarf mosaic virus, pathogens, range dynamics.

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Introduction

Recent decades have brought the emergence and spread of serious weed species in agricultural habitats across Europe (Weber & Gut, 2005) and, in several cases, such changes occurred relatively rapidly within a few decades. Prominent examples include the spread of *Ambrosia artemisiifolia* L., *Cyperus esculentus* L. and several Poaceae (e.g. *Panicum* spp., *Eleusine indica* (L.) Gaertn.) in parts of Central and Eastern Europe (Jehlik, 1998; Dancza *et al.*, 2004; Essl *et al.*, 2009). Albeit the underlying causes are context-specific, it has become evident that in most cases, their spread seems to be fostered by their tolerance to herbicide application, agricultural practices (intensified maize production in crop rotation systems, conservation vs. conventional tillage) or evolutionary changes within a weed species (Clements & DiTommaso, 2011). Many of these species are adapted to warm climates, and hence there are indications that climate change may foster their spread further (Essl *et al.*, 2009).

Correspondence: Dr S Follak, Austrian Agency of Health and Food Safety, Spargelfeldstraße 191, 1220 Vienna, Austria. Tel: (+43) (0) 50555 33347; Fax: (+43) (0) 50555 95 33330; E-mails: swen.follak@ages.at; follaksw@web.de

Sorghum halepense (L.) Pers. is a serious perennial weed species worldwide, particularly in humid warm-temperate and subtropical regions (McWorther, 1989). It may cause substantial yield loss in several crops. Williams and Hayes (1984) reported that heavy infestation in soybean (*Glycine max* L. Merr.) reduced yields by 59% to 88%, and Mitskas *et al.* (2003) have shown that yields of grain maize (*Zea mays* L.) can drop by 57% to 88%. Plants that emerged from rhizomes are more competitive than seedlings, because of their faster growth rate, even under stress conditions (Mitskas *et al.*, 2003; Acciaresi & Guiamet, 2010). In addition, *S. halepense* may serve as a host and reservoir for several pathogens that may attack crop plants (McWorther, 1989). The ability of *S. halepense* to regenerate even from small rhizome fragments and its prolific seed production severely limits the potential for successful control (Warwick & Black, 1983).

In south-eastern and southern European countries, *S. halepense* is widely established in agricultural areas. For example, *S. halepense* is frequently found in fields in Slovenia (Jogan *et al.*, 1999). In Hungary, after rapid spread beginning in the mid-1960s, *S. halepense* has become one of the most important weeds (Novák *et al.*, 2009). In Austria, as in remaining Central Europe, recent studies have shown that habitat affiliation seems to change and that distribution of *S. halepense* has recently increased (e.g. Essl, 2005; Weber & Gut, 2005). Hence, it may be argued that further spread may create severe agricultural problems in Central Europe. Analysing the invasion history of alien species may provide important insights into spatio-temporal patterns and dynamics of spread may help to identify underlying mechanisms and provide evidence for assessing the potential of further expansion (Lavoie *et al.*, 2007; Essl *et al.*, 2009). In such a sense, retrospective analyses of invasions are crucial for assessing impacts and identifying management strategies. Here we provide an analysis of the invasion history and the impacts of *S. halepense* in agriculture in Austria. This study is based on an exhaustive distribution data set (including information on its distribution, habitat affiliation, invasion status) that allows the analysis of the spatial-temporal spread and the extent of crop infestation and on a case study of the importance of *S. halepense* as a reservoir for pathogens. In particular, we address the following questions: (i) What is the spatio-temporal pattern of spread? (ii) If and to what extent did the importance of agricultural habitats for the species increase across time? (iii) Does *S. halepense* serve as a reservoir for pathogens that are problematic for maize cultivation? (iv) What is the potential of further spread and what are the concurrent implications for agricultural impact?

Materials and methods

Study species

Sorghum halepense is assumed to be native to the Middle East, Central Asia and the Indian subcontinent (GRIN, 2012), although after long-lasting human-mediated dispersal, its current distribution is near-cosmopolitan and there remains some uncertainty regarding its native range. *Sorghum halepense* is a fast-growing, competitive C_4 perennial Poaceae that combines sexual and vegetative reproduction, the latter being particularly important for the establishment of dense populations (Warwick & Black, 1983; McWorther, 1989). This species is best adapted to humid summer rainfall regions in warm-temperate to subtropical regions, although more cold-tolerant ecotypes have emerged during the last decades (Warwick & Black, 1983).

Study area

Austria is a land-locked country in Central Europe with a population of slightly more than eight million inhabitants mainly living in the lowlands and in the major valleys of the Alps. The country encompasses a total area of 83 858 km^2. Two-thirds of Austria is dominated by mountainous regions. The climate is temperate in the lowlands, being more continental in the east (annual precipitation: 500–700 mm) and more humid in the western, northern and southern regions (annual precipitation: 700–1200 mm). In higher altitudes, the climate is increasingly harsh and precipitation increases. The landscape at low to medium altitudes is shaped by a long tradition of agricultural land use.

Data sources and analysis

We used the distribution data set of Essl (2005) as a basis and updated it to cover the time period until 2011. Additional data were taken from the floristic literature and national and international databases (Virtual Herbarium, http://herbarium.univie.ac.at/database/; ZOBODAT, http://www.zobodat.at/; GBIF, http://www.gbif.org/). These data were supplemented by unpublished data from botanists and experts (see acknowledgements). The use of distribution data may suffer from spatially and temporally biased sampling. However, *S. halepense* is a conspicuous species that has been intensively collected and studied in Austria, since its first introduction in the nineteenth century (Essl, 2005). Further, the exhaustive use of several sources should have minimised sampling bias. In total, 302 records of *S. halepense* were collated. The majority of these records were unpublished (132 records), followed by records from the floristic literature (122 records) and databases (48 records). All of these records have been assigned to a grid cell (5 × 3 geographic minutes, *c*. 33 km^2) of the Floristic Mapping Project of Central Europe (FMA; Niklfeld, 1998). For each record, the status of the respective population, whether established or casual, had been assessed using the documented size of the population in the original data source. A population with more than 100 reproductive individuals was classified as established and when the descriptive information in the original data source indicated a large population. Smaller populations were only classified as established, if at least two records in consecutive years had been reported. Populations which we could not classify unambiguously and records without any information have been classified as casual. Data on colonised habitat types has been extracted from original data sources and assigned to the following two categories: fields (within or at the field margin) and outside fields (i.e. urban waste land, roadsides, railways).

To reconstruct the invasion history, we mapped the total distribution and the occurrence within fields or outside fields for three time periods (< 1970, 1971–1990 and 1991–2011). For the analysis of invasion rates in Austria and across habitat types, we used invasion curves according to Pyšek and Prach (1993). For occurrences in fields, we additionally collected information on the invaded crop species. To evaluate the area of the crops being most at risk to be invaded by *S. halepense*, we used the data of the Integrated Administration and Control System (IACS) for the year 2010 from the Austrian Ministry of Agriculture (BMLFUW). The IACS provides spatially explicit information on the crop type for each field parcel and each year. To investigate the importance of *S. halepense* as a reservoir for pathogens, we conducted a case study and analysed the prevalence of the maize dwarf mosaic virus (MDMV) in populations in southern Austria. This virus is a serious pathogen affecting maize worldwide (McWorther, 1989). In 2011, leaf samples from 21 locations in southern Austria were randomly collected and were tested for MDMV using an ELISA test kit (Agdia Inc., Elkhart, Indiana, USA). Serological analysis was performed following the conditions recommended by the manufacturer. Reactions were measured spectrophotometrically at 405 nm. Samples with $A_{405nm} > 3 \times$ negative control were considered to be positive.

Results

Spatio-temporal patterns of spread

In Austria, *S. halepense* was first recorded in 1871 in Upper Austria near the city of Wels (Hohla *et al.*, 2009). The next record is a herbarium specimen from 1890 collected in Vienna (deposited at the herbarium of Karl–Franzens-University of Graz, GZU). Until 1970, records remained rare and had been found primarily in large cities (Graz, Vienna, Salzburg) (Fig. 1A). Until the end of 1960s, the increase in cumulative numbers of records was linear (Fig. 2). The spread of *S. halepense* across Austria gained momentum after 1970 (Fig. 1B) and the cumulative number of records increased exponentially (Fig. 2). More recently, *S. halepense* has expanded strongly in the lowlands of southern, eastern and northern Austria; > 70% of all records have been collected since 1990 (Figs 1C and 2). The majority of the early records were classified as casual. First records of established populations were recorded in the lowlands of southern Austria at the end of the 1970s and approximately 25% of the total number of records was categorised as established. In southern Austria (Styria) in the period of 2000–2011, the number of established populations was 56, which is > 80% of all records in this period. Thus, established populations have increased significantly faster than casual populations.

Habitat affiliation

At about the same time that the total number of records started to increase exponentially, the first records of populations in fields were made in southern Austria, in Styria in 1972 (Ries, 1992) and subsequently in other parts of Styria (Melzer, 1982). However, the cumulative number of records in fields increased slowly until 2000 (Fig. 2). Since then, *S. halepense* has invaded agricultural habitats much more frequently (4/5 of all records in fields have been collected since 2000) and records in fields now account for 32% of all records. However, the occurrence of *S. halepense* in fields is still mostly restricted to southern Austria (Styria) (83% of all records in fields), albeit recently in eastern Austria several records have been made in fields.

Agricultural impact

In Austria, *S. halepense* was predominately found in grain maize and oil-pumpkin (*Cucurbita pepo* L.) and only rarely in other crops, for example, potatoes (*Solanum tuberosum* L.), sorghum (*Sorghum bicolor* agg.) or on fallow land. To evaluate the area of grain maize and oil-pumpkin fields at risk to invasion by *S. halepense* in southern Austria, we calculated their cultivated area (based on the database of the IACS) for the year 2010 for each grid cell where *S. halepense* has already invaded fields (Fig. 3). We found that *S. halepense* invasion puts 17635 ha of grain maize fields (41% of the total grain maize area in Styria) and 6160 ha of oil-pumpkin fields (40%) at risk in southern Austria (Fig 3.). In the same region, we tested for the importance of *S. halepense* as a

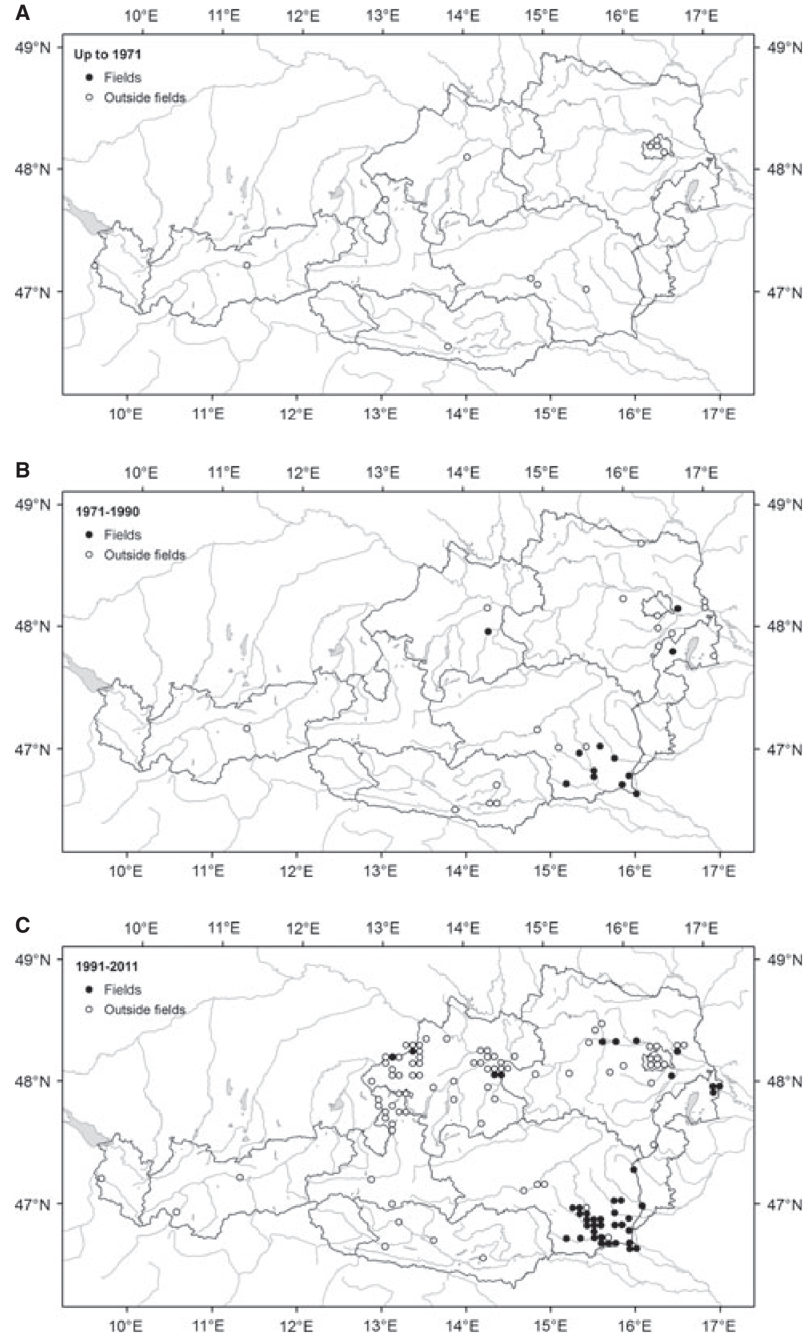

Fig. 1 Grid distribution maps of *Sorghum halepense* in Austria for the time periods (A) up to 1970, (B) 1971 to 1990 and (C) 1991 to 2011 based on the grid (5 × 3 geographical minutes, *c.* 33 km^2) of the Floristic Mapping Project of Central Europe (Niklfeld, 1998).

reservoir for MDMV. In the 21 samples collected in 2011, MDMV was recorded in 8 samples (38%) (Fig. 4).

Discussion

Spatio-temporal patterns of spread and habitat affiliation

The invasion of *S. halepense* in Austria exhibited a significant time-lag of *c.* 100 years between first record and the onset of rapid spread and the occurrence of first established populations. Such prolonged time-lags have been frequently observed in plant invasions (Kowarik, 1995; Křivánek *et al.*, 2006; Essl *et al.*, 2009) and they may mask the true spread potential of an alien species. In Austria, first records of *S. halepense* were nearly all in ruderal habitats and for larger cities and hence were probably related to repeated human-assisted long-distance dispersal via contaminated seeds. The saturation phase of spread has not been reached, as the number of

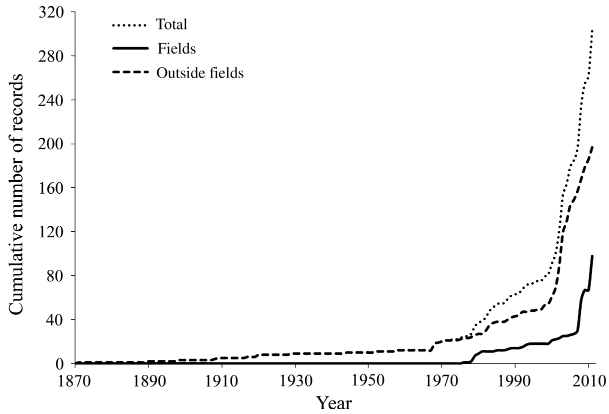

Fig. 2 Cumulative numbers of records of *Sorghum halepense* in Austria, given for records within and outside fields, as well as the total numbers of records.

records has increased substantially in the last decade. The range expansion in Austria has been accompanied by a niche expansion, that is, *S. halepense* has been able to expand into previously uncolonised habitats like crop fields.

The results indicate that the phase of rapid spread of *S. halepense* was delayed in Austria, compared with the neighbouring countries to the east and south. In these countries, the invasion of *S. halepense* in fields appears to have taken place much earlier than in Austria. In southern Slovakia, first records in fields were collected in 1954 (Komárno District, Jehlik, 1998), although *S. halepense* remained rare there until recently (Májeková & Zaliberová, 2008; Kropáč & Mochnacký, 2009). In Slovenia, *S. halepense* has colonised fields since the 1960s and the invasion advanced from the south to the north (Jogan *et al.*, 1999). In Hungary, *S. halepense* started to invade fields also in the mid-1960s and it seems that it is already entering the saturation phase in fields (Novák *et al.*, 2009). In northern Italy, *S. halepense* has been known since the middle of the nineteenth century and is now common in ruderal habitats (river embankments and roadsides) and fields (e.g. Poldini *et al.*, 1998; Wilhalm, 2001).

A rapid spread of populations of *S. halepense* to fields in adjacent grid cells occurred, in particular, in southern Austria (Fig. 1A and B). It seems likely that

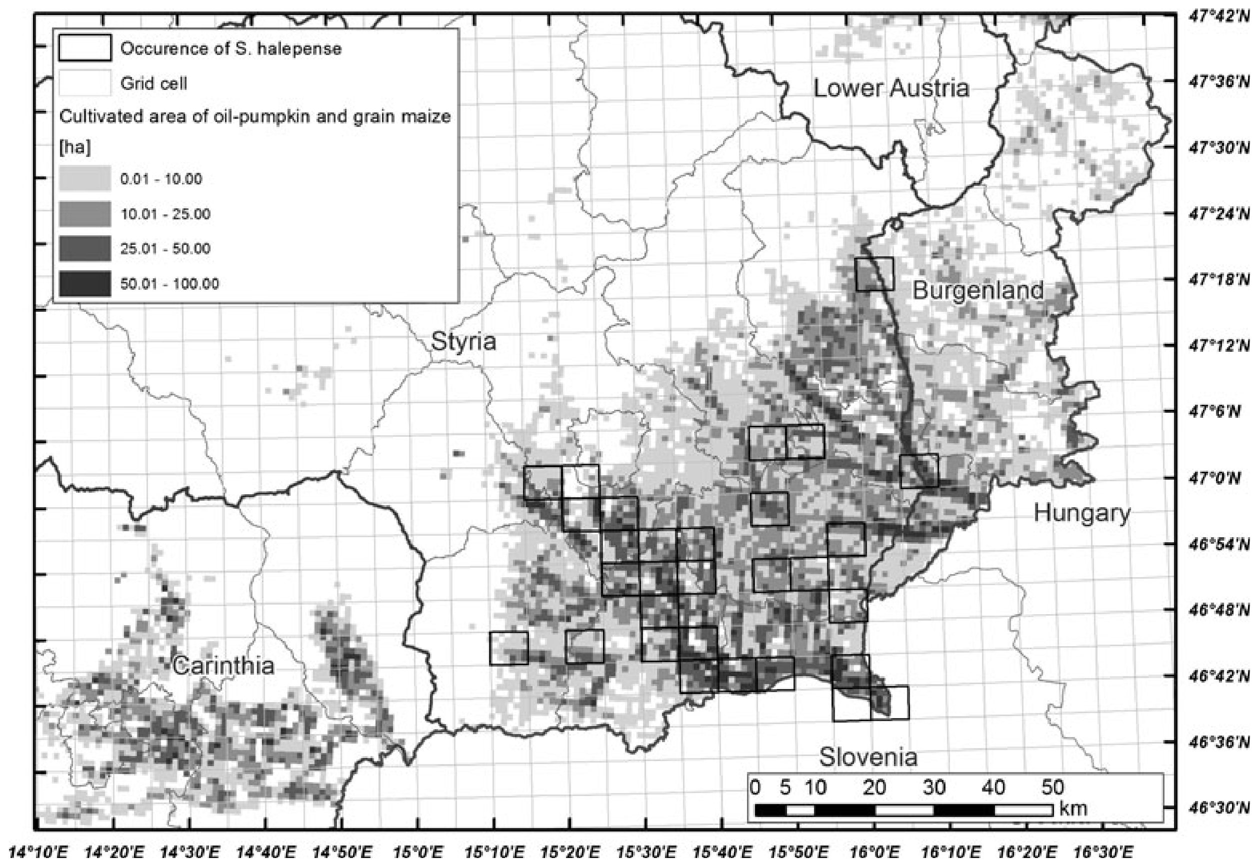

Fig. 3 Area of grain maize and oil-pumpkin fields (based on IACS) for the year 2010 in southern Austria. Crop area (1 × 1 geographical minutes, *c.* 2 km^2) and the distribution of *Sorghum halepense* (5 × 3 geographical minutes, *c.* 33 km^2) to identify crop area at risk to be invaded by *S. halepense* are illustrated. Only in-field records since 1991 are shown.

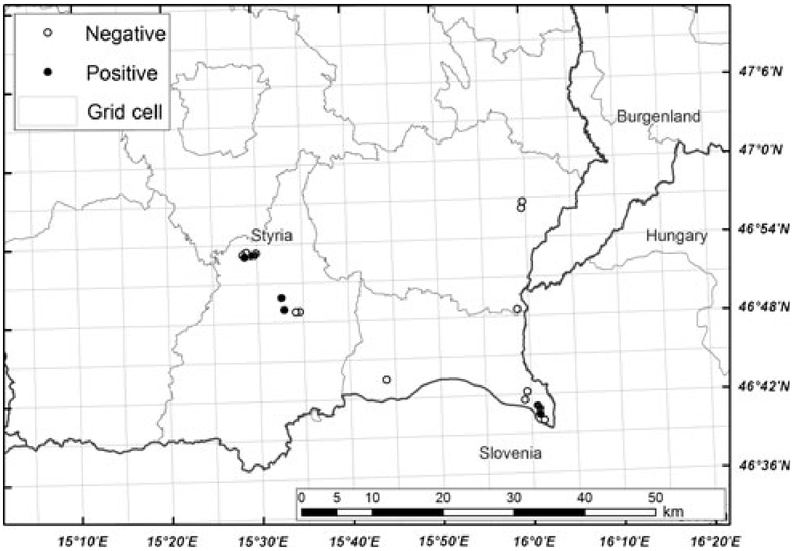

Fig. 4 Location of the samples of *Sorghum halepense* analysed for the maize dwarf mosaic virus (MDMV). Samples positive for MDMV are shown with black circles; samples negative of MDMV are represented by white circles.

due to the connectivity of this habitat in this region (Fig. 3), spread across grid cells occurred quickly. This occurrence pattern suggests that range filling and regional expansion was fostered by frequent unintentional human-mediated dispersal. Ghersa *et al.* (1993) showed that a maize harvester dispersed seeds of *S. halepense* within a field up 50 m from a source population. Moreover, rhizomes and seeds can be transported from field to field over longer distances attached to agricultural machinery, creating new nascent foci; rhizome fragments can regenerate very easily (Warwick & Black, 1983). Such dispersal processes have been also shown to facilitate the invasion of other perennial agricultural weed species, for example, *Solanum carolinense* L. (Follak & Strauss, 2010) or *Cyperus esculentus* L. (Dancza et al., 2004). *Sorghum halepense* is difficult to control and it is sensitive only to specific, high-cost, post-emergence herbicides. So, Novák *et al.* (2009) argue that the expansion of *S. halepense* in Hungary was promoted by extensive maize monoculture farming and widespread use of triazine herbicides, which had no effect on *S. halepense*. In cooler regions of Austria (e.g. Upper Austria), the invasion of *S. halepense* seems to be limited by climatic constraints. This may be partly due to the frost sensitivity of the rhizomes (Stoller, 1977) and the overall high thermal growth optimum (Warwick & Black, 1983).

Agricultural impact

Although interference studies under Central European conditions are lacking, there is little doubt that the impact of *S. halepense* on crop yields can be significant (Williams & Hayes, 1984; Mitskas *et al.*, 2003). At present, *S. halepense* is most troublesome in the southern lowlands of Austria, where it has recently established dense populations in fields. Likewise in other countries (Novák *et al.*, 2009), spring-sown crops like maize are most at risk of being invaded. Moreover, our data show that *S. halepense* serves as an important reservoir for the vector-transmitted maize dwarf mosaic virus (MDMV). The occurrence of MDMV in Europe is known to be closely linked to the presence of *S. halepense* (Achon & Sobrepere, 2001). In northern Italy (Friuli-Venezia Giulia) and Serbia (Vojvodina), where *S. halepense* is already widespread (Poldini *et al.*, 1998; Vrbničanin *et al.*, 2009), MDMV was commonly found on maize plants (Ivanovic *et al.*, 1995). In Hungary, the prevalence of MDMV in maize fields varied between 7% and 86%, and, depending on the maize cultivar, total yield losses up to 30.5% were documented (Peti, 1983). These results make it likely that MDMV may be transmitted to maize, potentially adding additional indirect negative effects on yield losses from competition.

Potential future spread and management recommendations

The current distribution pattern of populations of *S. halepense* in Austria shows that records are most frequent in the eastern and southern lowlands, which are the warmest parts of Austria (Fig. 1C). Although the invasion of *S. halepense* still seems to be limited by climatic constraints in cooler regions of Austria, the rapid spread during the last decades and the on-going niche-shift towards fields in the Austrian lowlands suggest that incipient climate change may have begun to elevate this constraint. Using a niche-based habitat modelling approach, Kleinbauer *et al*. (2010) have shown that annual mean temperature is a key limiting factor for *S. halepense* in Germany and Austria. They also report that rising temperatures will increase habitat suitability strongly and even under most moderate climate change scenarios, all major agricultural areas will become climatically suitable by 2050. In Europe, *S. halepense* is already common in agricultural areas with a slightly warmer climate, like in Hungary (Novák *et al*., 2009) and Slovenia (Jogan *et al*., 1999). In the invasion hotspots in southern Austria, the majority of the cultivated grain maize and oil-pumpkin area is currently not invaded. However, as dispersal limitation may delay range filling on landscape scales (e.g. Essl *et al*., 2012), further spread in fields is probable. This is more likely, as the area of oil-pumpkin and maize has been expanded in the last years (Statistik Austria, 2012).

A strategy to slow or even reverse future spread of *S. halepense* invasion needs to take several elements into account. In particular, it is crucial to avoid the transport of seeds and rhizomes from field to field. This can be achieved by thoroughly cleaning machinery and harvesting equipment. Small infestations can be eradicated mechanically (by removing the plants including its rhizomes). However, this effort needs to be reinforced over several years to avoid that remaining rhizome fragments resprouting. Larger populations (e.g. along roadsides, field margins) can be managed with repeated mowing, which reduces rhizome growth and prevents seed onset (Warwick & Black, 1983). Large populations in fields can only be managed with herbicides. The effectiveness of different herbicides has already been tested (Torma *et al*., 2006). As *S. halepense* is sensitive only to specific herbicides (e.g. chloracetamide, graminicides like fluazifop-P or clethodim, different sulfonylurea active ingredients), control entails additional costs for the farmer.

Conclusions

There is substantial evidence that *S. halepense* may emerge as a major weed in crop fields in the near future in Austria, and most probably also in other parts of Central Europe (e.g. Germany, Czech Republic). If *S. halepense* spreads northward, in particular, into traditional maize growing regions, there will be much concern about the impact such a change in distribution might have on maize production. *Sorghum halepense* is already well-established in parts of Austria, although it is absent or rare in most regions. This situation still provides a window of opportunity for management. If management measures are consequently implemented (e.g. surveillance and use of effective herbicides), there is a substantial chance to limit further spread. However, the rapid spread process calls for rapid implementation of control measures, as prospects for successful management decrease with further spread.

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