Drivers of *Ambrosia artemisiifolia* abundance in arable fields along the Austrian-Hungarian border

Faktory určující abundanci *Ambrosia artemisiifolia* na polích podél rakousko-maďarských hranic

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The Carpathian Basin is one of the most important regions in terms of the invasion of the common ragweed (*Ambrosia artemisiifolia*) in Europe. The invasion history of this weed, however, seems to have been assessed differently in Austria and Hungary: scientists in both countries assumed that this species had become abundant earlier and had caused more problems in their own than in other country. The goal of this study is to resolve the historical misunderstandings and scrutinize the related popular beliefs by a concise literature overview and an extensive analysis of the current patterns in ragweed infestations in crops in the borderlands in eastern Austria and western Hungary. The abundance of *A. artemisiifolia* was measured in 200 arable fields across the region, along with 31 background variables. Data were analysed using binomial generalized linear models (GLM), decision tree models and variation partitioning. *Ambrosia artemisiifolia* occurred more frequently in Hungary, but there were no significant differences in the proportion of larger cover values recorded in these two countries, and 'cover values > 10%' were even slightly more common in Austria. We found that previous crops of maize and soya bean and conventional farming were associated with the higher abundances in Austria, while organic farming was associated with relatively higher frequencies of heavy infestations in Hungarian fields. In the overall analysis crop cover was the most important variable with low crop cover associated with high ragweed abundance. Temperature and phosphorous fertilizer were negatively, while precipitation and soil phosphorous concentration positively associated with the abundance values. Land-use variables accounted for more of the variance in the abundance patterns of common ragweed than environmental variables. The current patterns in ragweed distribution might indicate that a saturation process is still underway on the Austrian side. The saturation lag of 20–30 years is possibly due to several factors and the role of the Iron Curtain in determining cross-border exchange of propagules could be decisive. Nevertheless, the discrepancies uncovered in the accounts of the invasion of Hungarian and Austrian authors might also be seen as legacies of the Iron Curtain, which were caused by mutual limitations on access to national data and literature of the other country in a critical period of rapid ragweed spread. These discrepancies, that had a long-lasting effect on the work of scientific communities, are documented here in detail for the first time.

Keywords: agriculture, arable fields, common ragweed, invasion, invasive plants, ragweed, spread, weed distribution, weed ecology

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Introduction

The spread of alien species is a global phenomenon with detrimental impacts on human societies (Early et al. 2016, Pyšek et al. 2017). According to the definition of plant invasion, an introduction favoured by man occurs when the propagules of a species arrive at a site beyond its previous natural geographical range and establish reproducing populations in the wild, thus overcoming geographical and environmental barriers. The spread of an alien species depends, in principle, on the match between its ecological requirements and the local environment (Richardson et al. 2000, Richardson & Pyšek 2006, 2012). Thus, considering that the natural range of a species does not reflect political borders the ranges in physical and biological factors (soil, climate, competitor species etc.) in such areas should be more important than political ones.

Common ragweed (*Ambrosia artemisiifolia* L.), a noxious arable weed of North American origin, is currently spreading all over the world (Makra et al. 2015, Montagnani et al. 2017). Because of its highly allergenic pollen, negative effects on biodiversity and the yield of agricultural crops, ragweed has recently become the focus of scientific research (Essl et al. 2015, Alberternst et al. 2016). Although climatic constraints will limit its final distribution, common ragweed is still spreading both at global and local scales (Essl et al. 2015, Ortmans et al. 2017). This spread is likely to be further facilitated by climate warming (Storkey et al. 2014, Case & Stinson 2018, Mang et al. 2018) and by the ability of this species to quickly adapt to new environmental conditions (Li et al. 2015, Scalone et al. 2016, Onen et al. 2017, Gorton et al. 2018, van Boheemen et al. 2019). Rapid ragweed spread is often associated with major socioeconomic transitions causing an increase in the amount of disturbed land (Kiss & Béres 2006). Even if the ragweed invasion is now a global issue, studying its distribution at regional scales might provide a better understanding of the reasons for its successful spread and identify why it is abundant in invaded areas.

In central Europe, Hungary is one of the most highly ragweed-infested countries (Kazinczi et al. 2008a) and is considered to be the centre of ragweed invasion and a major source of ragweed for neighbouring countries (Fenesi & Botta-Dukát 2011). Currently, in neighbouring Austria it is only common in agricultural habitats in the eastern and south-eastern lowlands (Essl et al. 2009, Mang et al. 2018). Although the invaded regions in the two neighbouring countries have largely similar macroclimatic, soil and land-use characteristics, the invasion history of ragweed seems to have been different in the two countries, unfortunately, in a highly contradictory and contested way. Although the scientists in Austria and Hungary provide accounts of the ragweed invasion in the whole region, the two accounts are highly incompatible (see Fig. 1 in Mang et al. 2018 versus Fig 1 in Fenesi & Botta-Dukát 2011, Fig. 4/2 in Novák et al. 2011 and Fig. 1 in Novák et al. 2014).

In Hungary, the first sporadic occurrences of common ragweed (from 1907 to 1927) in the Carpathian Basin are well documented by Csontos et al. (2010). According to Priszter (1960), from 1922 this species spread along a wide and continuous line and occupied the entire south of the Transdanubian region by 1959. Its dissemination was clearly associated with the newly introduced socialist type of large-scale agriculture, which is reflected in this weed's popular name, Stalin weed, in some newly invaded Hungarian regions (Kiss & Béres 2006). It became widespread between 1966–1977 and was by 1970 the 8th most abundant arable weed in Hungary (Novák et al. 2011). After the temporary political and farming crisis in the 1990s ragweed was reported to be the most predominant arable weed in Hungary (Novák et al. 2011, 2014).These reports state that the spread of this species was similar in most of the neighbouring countries, except Austria, where "unchanged landscape management standards" actually prevent the spread of this weed (Kiss & Béres 2006, p. 2156).

In Austria Essl et al. (2009) and Mang et al. (2018), report longstanding major ragweed problems in fields in the eastern and south-eastern parts of this country, going back to the 1970s. Nevertheless, in referring to neighbouring countries Mang et al. (2018) suggest that ragweed was first recorded only after 1990 throughout almost the whole of Hungary and a high occurrence in Austria before 1990. This divergent assessment of the ragweed situation may have been created and maintained by an asymmetric partial access to relevant data and literature sources on both sides of the border.

In addition to this divergence in the scientific accounts there also exists a long-standing popular opinion in Hungary that "ragweed is very common in Hungary, but it is almost missing from Austria", and that "ragweed and its associated health problems are considerably less when one crosses the border into Austria" (Kiss & Béres 2006). This widespread myth might possibly be due to the present or past experiences of people (e.g. allergic people vacationing or farmers commuting regularly between the two countries). The differences are typically attributed to the carelessness and bad practices of the Hungarian farmers, which are sometimes discussed in a historical context (Kiss & Béres 2006) or in terms of the climate in Hungary, which is considered to be more favourable for ragweed. Nevertheless, the validity of this myth and its components have never been scrutinized scientifically.

In this paper, we aim to critically examine the popular beliefs outlined above, determine in which country common ragweed is more abundant in the border zone, and explore how the differences in land use in the two states could influence the abundance of this troublesome weed. For this, we analyse field data on ragweed abundances in an area spanning both sides of the Austrian-Hungarian border that includes a broad diversity of the environmental and management factors that potentially influence the spread of this species. Specifically, we seek answers to the following questions: (i) Does the overall extent of ragweed infestation differ in the border zones of the two countries? (ii) Are there any sets of environmental or management conditions under which there is a significant difference in the incidence of ragweed infestation in the two countries? (iii) Which factors influence the abundance of common ragweed in the whole area studied? (iv) Is land-use more influential than environmental factors in determining the patterns in the overall abundance of common ragweed? We discuss the results taking into consideration the different historical accounts published by Hungarian and Austrian scientists, and use our results to try and resolve the historical misunderstanding.

Materials and methods

Study area

To study the effect of differences in land-use practices and environmental conditions in the borderlands on the distribution of ragweed we investigated a strip of land extending approximately 30 km from the Austrian-Hungarian border into both countries (Fig. 1).

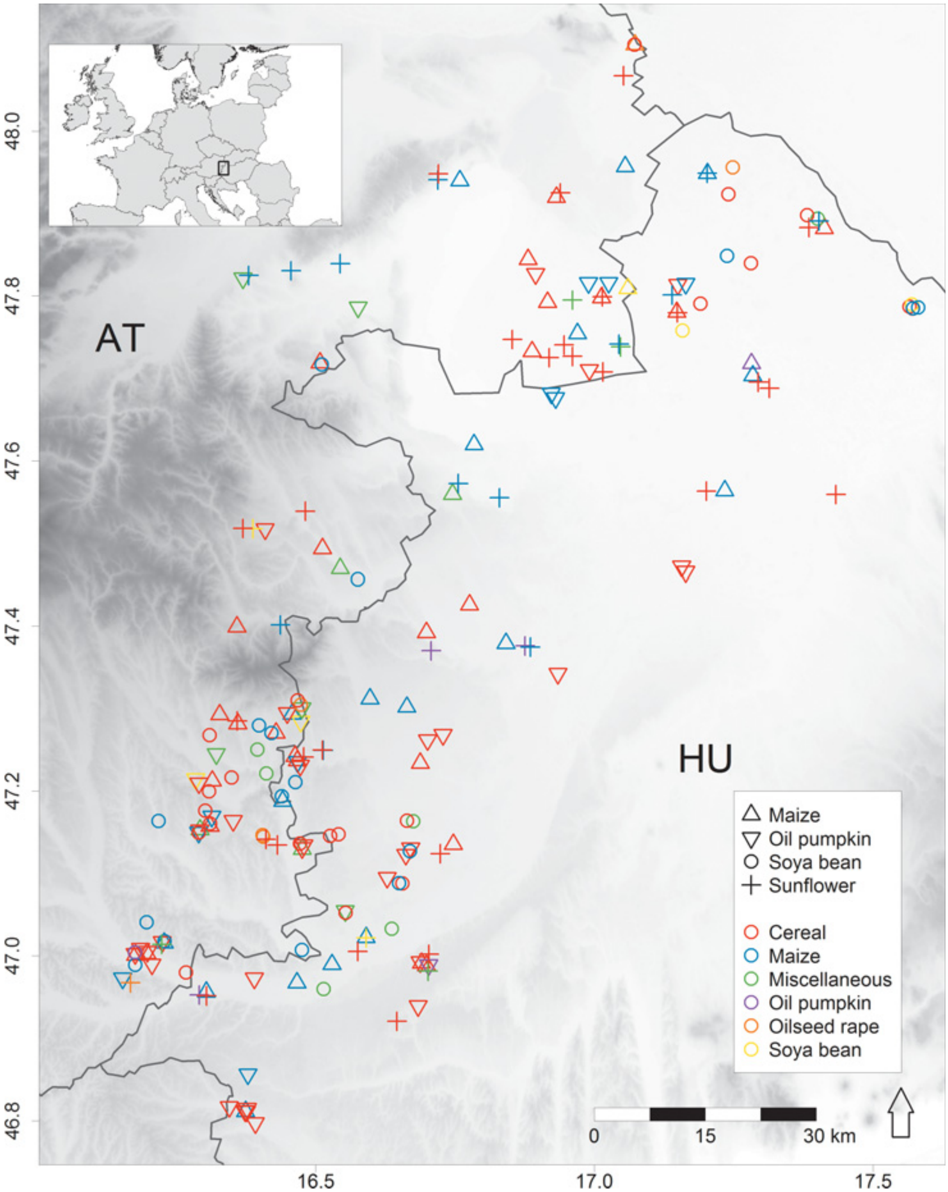


Fig. 1. – Map showing the distribution of the 200 fields surveyed along the Austrian-Hungarian border. Crop is indicated by the shape and preceding crop by the colour.

As the 355 km long borderline follows an irregular zigzag shape, this resulted in an area extending ~150 km N-S and 105 km E-W. The northern part of this area includes part of the Western Pannonian Plain and the south-eastern part of the Vienna Basin in Austria and the western part of the Little Hungarian Plain in Hungary. Towards the south plains are increasingly replaced by the foothills of the Eastern Alps, which extend well into

Hungary with slightly decreasing altitudes (for more information about the altitudinal ranges, as well as climatic and soil parameters in the study area see Table 1). The study area is nested in a broader region with two major macroclimatic gradients: a global north-south temperature gradient and an east-west altitudinal (lowland/mountain) gradient. Since the borderline does not coincide exactly with either of these gradients, both macroclimatic gradients are present in both countries to almost their full extent and the influence of the country can be statistically decoupled from the macroclimatic gradients.

Data collection

First, we searched for farmers in the study area who permitted us to access to their fields and were willing to be interviewed about land-use factors. We focused on fields with four major regional crops, which were known to be sensitive to ragweed infestations: sunflower (*Helianthus annuus*), soya bean (*Glycine max*), maize (*Zea mays*) and oil pumpkin (*Cucurbita pepo*). Altogether, 200 fields were sampled (25 fields of each crop per country). Weed data were recorded between the years 2015 and 2018 at the seasonal peak of *Ambrosia artemisiifolia* in the months of July and August each year. Sampling was done in four 50 m^2 (5 × 10 m rectangle shaped) plots within each field. One plot was located at the edge of a field (inside the outermost seed drill line) and the other three plots were located inside the fields at different distances (between 10 and 200 m) from the edge. In addition, plots were placed randomly both at the edges and in each field. In each plot the percentage ground covered by common ragweed (as well as other weeds) and the crop species were estimated visually. A soil sample of 1000 cm^3 from the top 10 cm layer was also collected from each field. Soil analyses were carried out in a laboratory of Synlab Hungary Ltd (https://www.synlab.hu).

Management variables, including the application of fertilizer, tillage and weed control in the fields studied, as well as factors describing their history (preceding crop) and ownership structure (field size, farm size) were obtained directly from the farmers in brief targeted interviews. In order to avoid rare levels of categorical variables, preceding crops occurring less than 10 times were considered to be miscellaneous, and due to the high number of herbicide ingredients only the number treatments applied to a given field was recorded. Five bioclimatic variables assumed to be relevant for *A. artemisiifolia* were obtained from the WorldClim 2.0 database (Fick & Hijmans 2017). These were two annual (mean temperature, precipitation sum) and three seasonal features of climate based on data from the 1970–2000 period interpolated at a 30 sec (~1 km) resolution. For each field the nearest values were extracted using R statistical software (R Core Team 2018) and its packages ‘raster’ (Hijmans 2017) and ‘sf’ (Pebesma 2018). Altogether 31 predictor variables were included in the analysis (Tables 1, 2).

Data analysis

Since the distribution of cover values was strongly right skewed and the dispersal and skewness were different in the two countries, the distribution could not be adequately characterized by a single number (such as the mean or median). To overcome this we selected four threshold limits (Th0: ragweed cover > 0% – i.e. ragweed is present; Th1: cover > 1%; Th5: cover > 5%, and Th10: cover > 10%) and treated them as binary variables (1 = cover value is above threshold limit, 0 = cover value is below or equal to the

Table 1. –The continuous variables included in the statistical analysis

Variable (unit)	Ranges in Austria	Ranges in Hungary
Environmental variables:		
Altitude (m)	117–429	111–292
Annual precipitation sum (mm)	558–766	536–755
Mean annual temperature (°C)	9.05–10.3	9.45–10.38
Maximum temperature in the warmest month (°C)	22.5–24.39	23.29–24.39
Minimum temperature in the coldest month (°C)	–6.8 to –5.59	–7 to –5.9
Mean temperature in the wettest quarter (°C)	17.01–19,95	17.51–19,93
Soil pH (KCl)	3.73–7.48	3.75–7.83
Soil texture (KA)	25–66	26–54
Soil properties ($g \cdot kg^{-1}$):		
Humus	0.87–16.2	0.7–4.24
$CaCO_3$	0.1–35.1	0.1–28.5
Soil properties ($mg \cdot kg^{-1}$):		
P_2O_5	20–1740	29.8–2920
K_2O	79.7–902	65.7–1050
Na	13.2–230	17.6–194
Mg	47.4–883	54.6–823
Land-use variables:		
Crop cover (%)	10–100	10–100
Field size (ha)	0.17–75	0.3–60
Farm size (ha)	2–1500	1.5–5500
Tillage depth (cm)	8–45	15–50
Amount of fertilizer ($kg \cdot ha^{-1}$):		
N	0–186	0–210
P_2O_5	0–130	0–144
K_2O	0–170	0–200
Cultivating tillage (times)	0–5	0–4
Manual weed control (times)	0–8	0–6
Pre-emergence herbicides (No. of ingredients)	0–3	0–4
Post-emergence herbicides (No. of ingredients)	0–6	0–7

Table 2. –The categorical predictors and the response variables included in the statistical analysis

Variable (unit)	Values
Country	Austria, Hungary
Plot location	edge, centre
Response variables (ragweed cover):	
Th0: ragweed present (cover > 0)	0, 1
Th1: ragweed cover > 1%	0, 1
Th1: ragweed cover > 5%	0, 1
Th1: ragweed cover > 10%	0, 1
Land-use variables:	
Crop	maize, oil pumpkin, soya bean, sunflower
Farming type	conventional, organic
Tillage system	no-tillage, ploughing
Preceding crop	cereal, maize, miscellaneous, oil pumpkin, oilseed rape, soya bean

threshold limit), thus characterizing each plot by four binary response variables. Furthermore, as the abundance of *A. artemisiifolia* was substantially higher at the edges than in the centres of fields (similar to our previous results; Pinke et al. 2011), the results for field edges and field centres were analysed separately. In this way we fitted all of the models described below to eight different combinations of four response variables (Th0, Th1, Th5, Th10) and two datasets (field edges and field centres).

To determine whether there are differences in ragweed abundance in the two countries binomial generalized linear models (GLM) with country as the only predictor variable were fitted. Then, to assess which of the background variables are associated with the potential differences between the crops in the two countries, similar GLM models were fitted in a tree-based framework using model-based recursive partitioning (Zeileis et al. 2008) with all land-use and environmental data as partitioning variables. This technique identifies subsets in the data (splitting it along any of the partitioning variables) with significantly different predictor-response relationships.

To identify the most important factors associated with ragweed abundance in the area studied we used decision tree (also known as classification and regression trees, CART) models. Decision trees have a relatively simple and transparent structure, which makes the interpretation of the patterns easy and straightforward. We used all land-use and environmental variables and also country as predictors for fitting the decision tree models, as in Pinke et al. (2011).

Finally, we assessed whether land-use or environmental variables had greater effects on the abundance of common ragweed. Likelihood-ratio R-squared values (McFadden 1974, Menard 2000) were calculated for the GLM models containing environmental or land-use variables, or both, and then variation partitioning was implemented based on the R-squared values. Since the number of variables differs in the two sets of predictors (11 environmental and 21 land-use variables), adjusted R-squared values (Walker & Smith 2016) were also calculated.

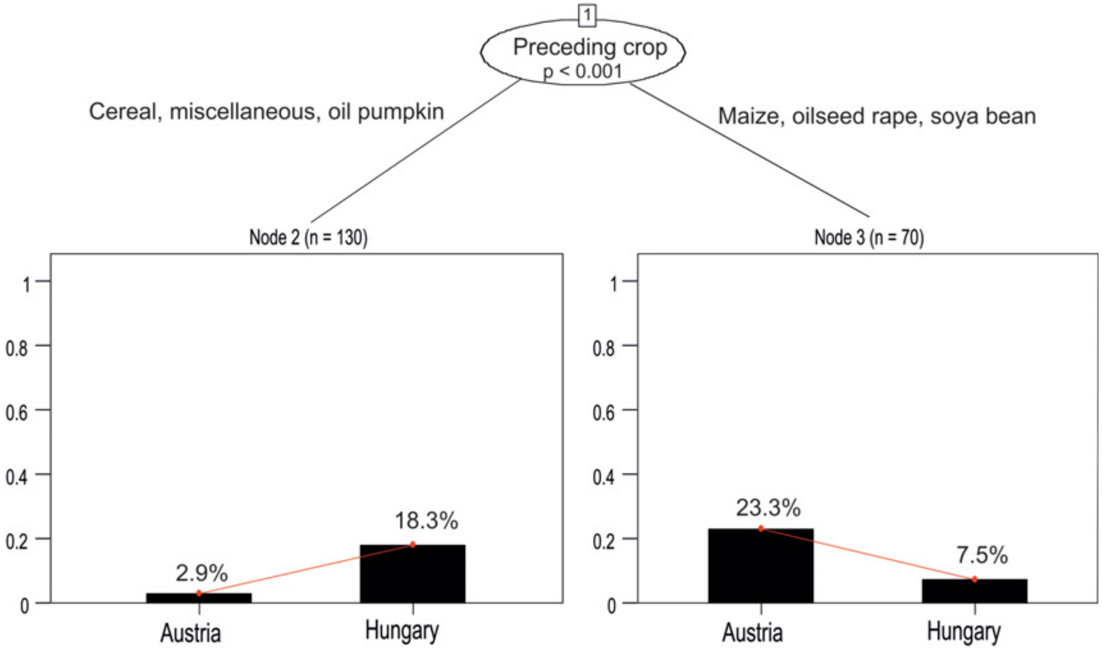
The entire statistical analysis was conducted in the R environment (R Core Team 2018) using the 'partykit' package (Hothorn & Zeileis 2015).

Results

The binomial generalized linear models (GLM) revealed that *A. artemisiifolia* occurred (Th0) significantly more frequently in Hungary both at the edges and centres of fields (Table 3). In the field centres the relatively low (1%, Th1) ragweed cover threshold was exceeded significantly more frequently in Hungary than Austria. Nevertheless, there were no significant differences in the proportion of large cover values recorded in the two countries and cover values > 10% (Th10) were even slightly more common at the edges and in the centres of fields in Austria.

Model-based recursive partitioning only identified significant differences between the two countries in two of the eight cases studied, both of them in centres of fields (Fig. 2). Preceding crop was an important factor for Th5 (ragweed cover > 5%) (Fig. 2A), whereas for Th10 (ragweed > 10%) both farming type and preceding crop were relevant factors (Fig. 2B). For Th5, if the previous crop was maize, soya bean or oilseed rape, a high (> 5%) ragweed cover was significantly more frequently recorded in Austria (23% in AT

(a) *Ambrosia* cover > 5% (Th5), field centres



(b) *Ambrosia* cover > 10% (Th10), field centres

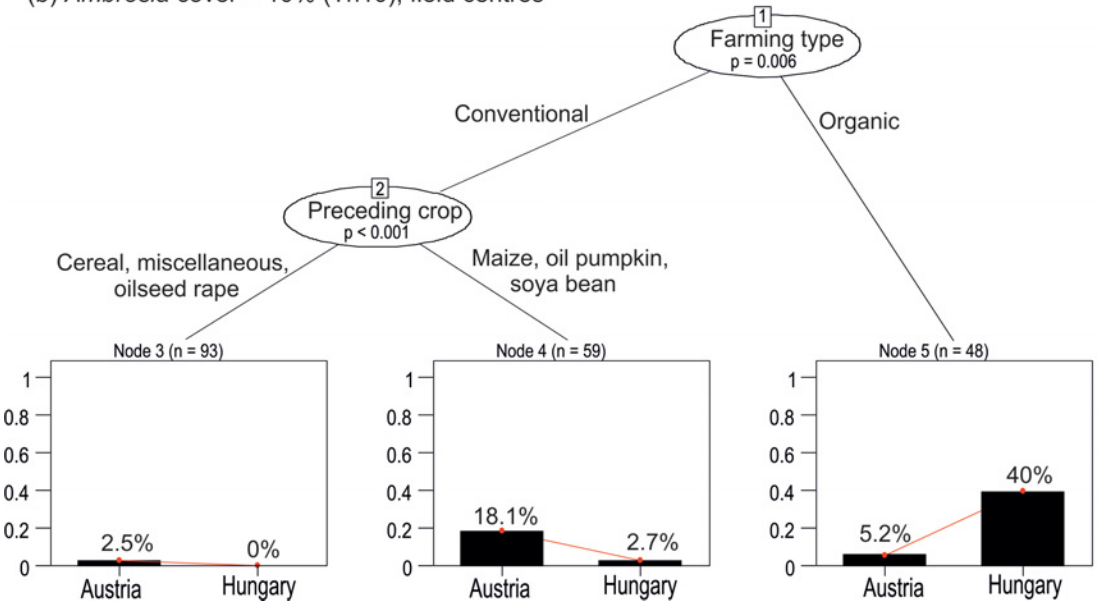
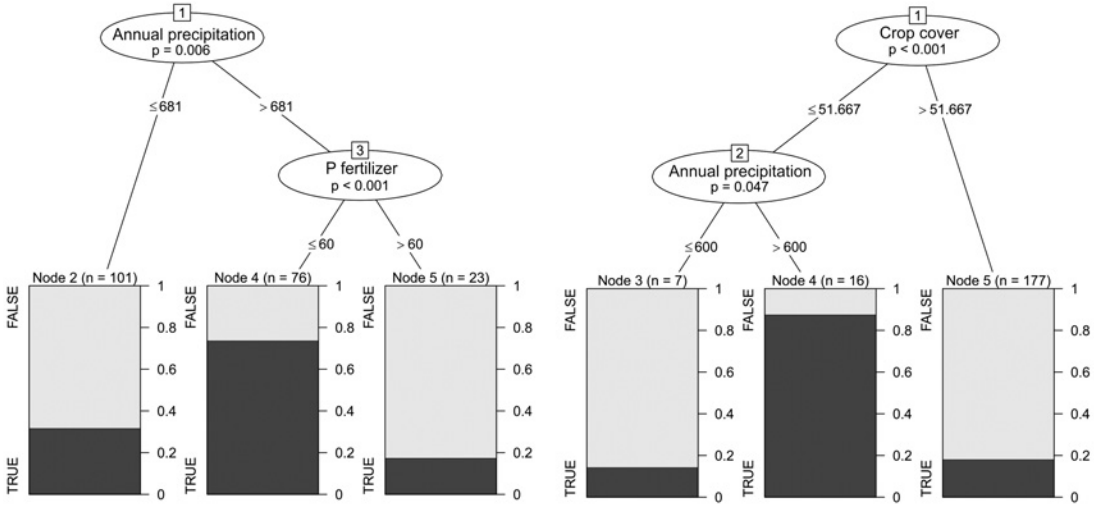


Fig. 2. – Model-based recursive partitioning results for the occurrence of *Ambrosia artemisiifolia* cover (Th5, Th10) in the centres of fields, highlighting the combinations of factors that lead to significant differences in the incidence of ragweed infestations in the two countries. The other six combinations of response variables and plot locations did not reveal any significant differences.


(a) *Ambrosia* present (Th0), field centres (b) *Ambrosia* cover > 1% (Th1), field centres

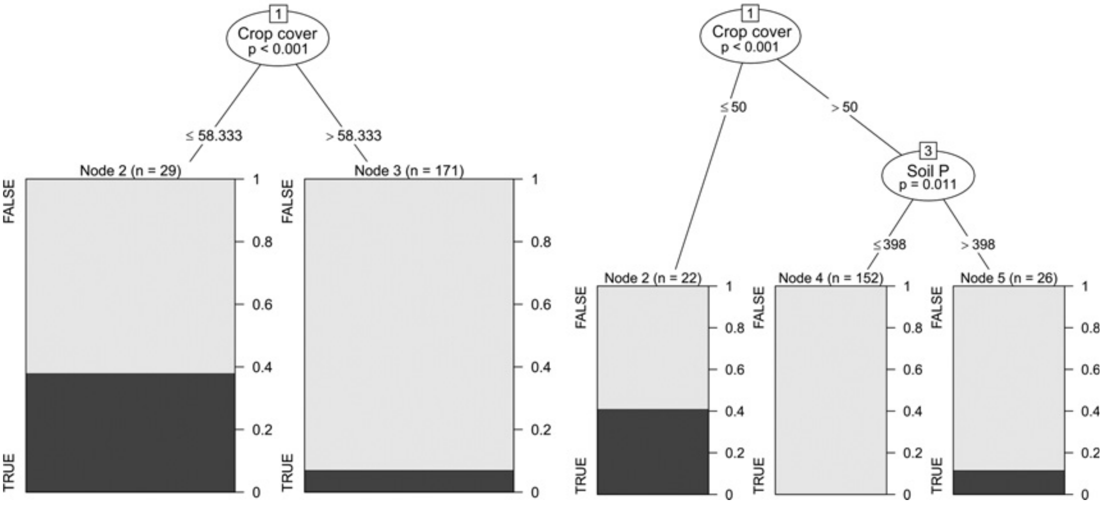
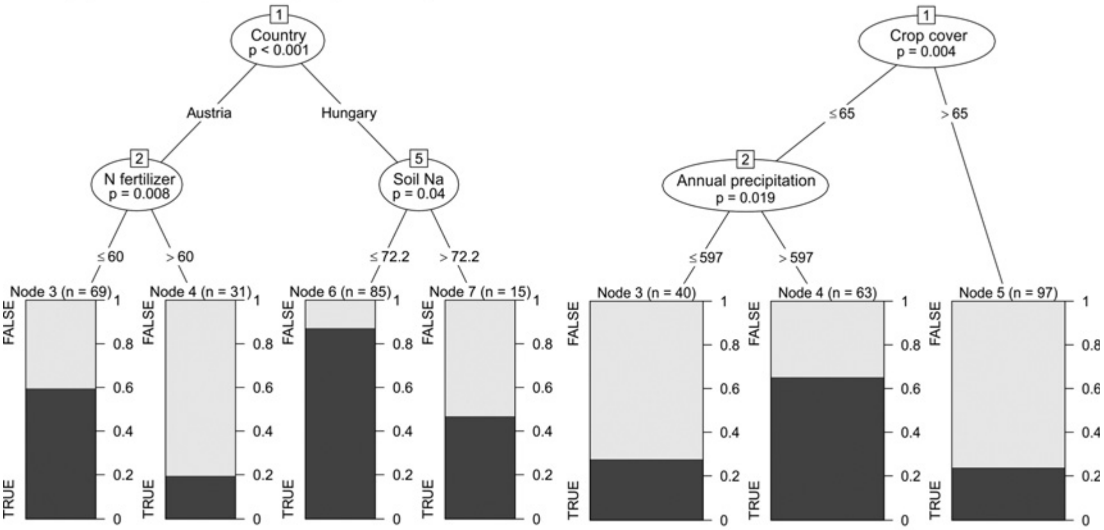

(c) *Ambrosia* cover > 5% (Th5), field centres (d) *Ambrosia* cover > 10% (Th10), field centres

Fig. 3. – Decision tree models of four abundance threshold limits for *Ambrosia artemisiifolia* recorded at the centres of fields.

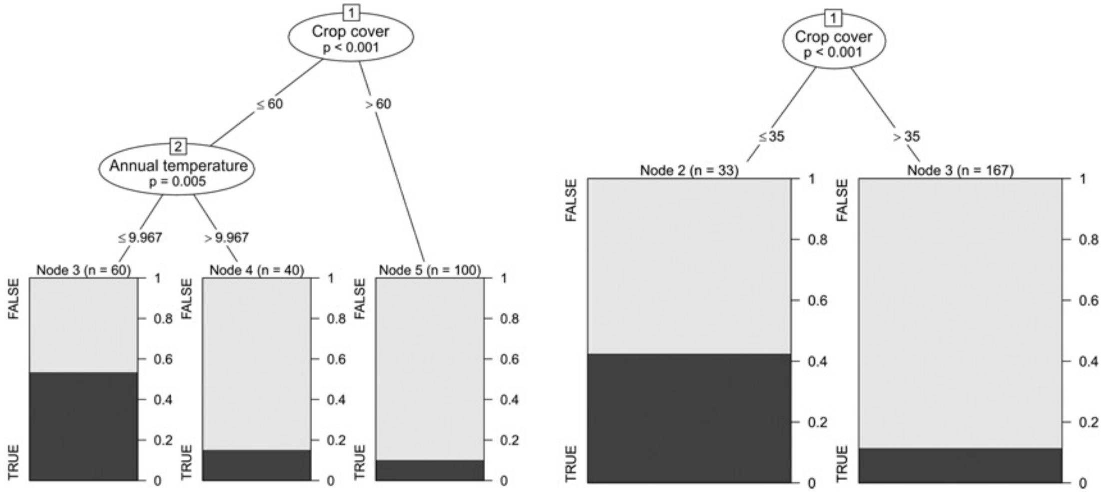
vs. 7.5% in HU), but if it was cereal or oil pumpkin the trend was opposite (2.9% in AT and 18.3% in HU, Fig. 2A). As for Th10, the highly infested fields were associated with organic farms in Hungary (40% in HU vs. 5.2% in AT) whereas in Austria it was with conventional farms with a preceding crop of either maize, soya bean or oil pumpkin (18.1 in AT vs. 2.7% in HU, Fig. 2B).

The decision trees revealed significant patterns in all of the eight cases studied (Figs 3–4). Country was associated with separation only once, though at first position regarding



(a) *Ambrosia* present (Th0), field edges

(b) *Ambrosia* cover > 1% (Th1), field edges



(c) *Ambrosia* cover > 5% (Th5), field edges

(d) *Ambrosia* cover > 10% (Th10), field edges

Fig. 4. – Decision tree models of three abundance threshold limits for *Ambrosia artemisiifolia* recorded at the edges of fields.

presence/absence values at the edges of fields (Fig. 4A). For Austria, subsequent splits were associated with application of N fertilizer with less frequent occurrence of ragweed in those fields treated with large amounts of fertilizer. In Hungary, the subsequent splitting variable was soil Na content, which was negatively associated with the occurrence of ragweed (Fig. 4A). In the other seven cases, the most influential variable was crop cover, which determined the highest number of splits in the tree models (six in the seven models, almost all at the first position), with lower crop cover values indicating high abundance of ragweed.

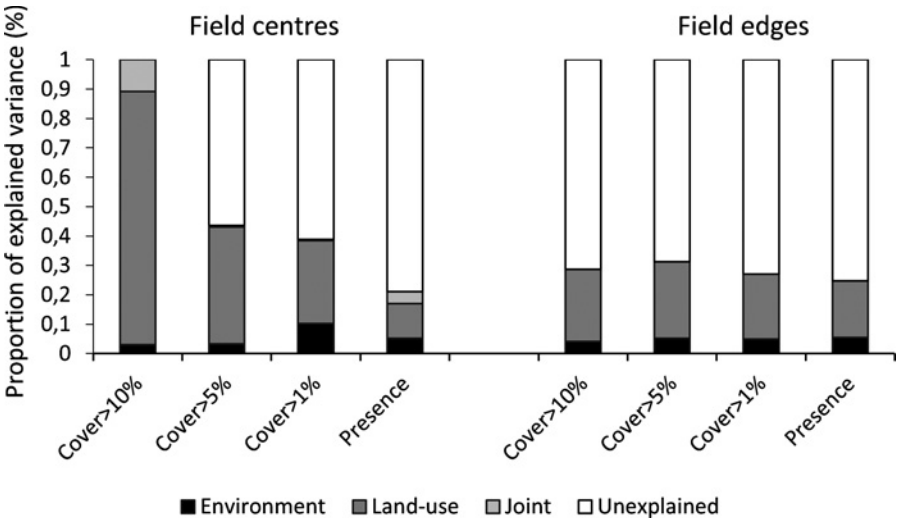


Fig. 5. –The variation partitioning using likelihood ratio- R-squared values.

Table 3. – Proportions of fields with the cover of *Ambrosia artemisiifolia* above the four threshold limits in Austria and Hungary and the results of comparing proportions using binomial generalized linear models (GLM).

Plot location	Response variable (threshold limits)	Proportion in Austria	Proportion in Hungary	Chi-square	P value
Field centres	*Ambrosia* cover > 10% (Th10)	7%	5%	0.35617	0.5506
	Ambrosia cover > 5% (Th5)	9%	14%	1.2369	0.2661
	Ambrosia cover > 1% (Th1)	16%	31%	**6.345**	**0.0118**
	Ambrosia present (Th0)	39%	53%	**3.9587**	**0.0466**
Field edges	*Ambrosia* cover > 10% (Th10)	17%	16%	0.036296	0.8489
	Ambrosia cover > 5% (Th5)	23%	25%	0.10967	0.7405
	Ambrosia cover > 1% (Th1)	31%	44%	3.6192	0.0571
	Ambrosia present (Th0)	47%	81%	**25.854**	**<0.0001**

Table 4. –The unadjusted and adjusted likelihood ratio-R-squared values of models of *Ambrosia artemisiifolia* cover with environmental and land-use variables. Unadjusted R-squared can be interpreted as the proportion of variation explained. Adjusted values reduce the number of predictors, thus their values may be negative, indicating that fitted variables explain less variation than expected in the case of random predictors.

Plot location	Response variable (threshold limits)	Environment		Land use	
		R^2	Adjusted R^2	R^2	Adjusted R^2
Centres	*Ambrosia* cover > 10% (Th10)	0.1381	-0.1043	0.9695	0.5289
	Ambrosia cover > 5% (Th5)	0.0388	-0.1154	0.4034	0.1231
	Ambrosia cover > 1% (Th1)	0.1063	0.0055	0.2870	0.1036
	Ambrosia present (Th0)	0.0922	0.0125	0.1585	0.0136
Edges	*Ambrosia* cover > 10% (Th10)	0.0415	-0.0813	0.2448	0.0215
	Ambrosia cover > 5% (Th5)	0.0520	-0.0478	0.2602	0.0787
	Ambrosia cover > 1% (Th1)	0.0488	-0.0343	0.2215	0.0704
	Ambrosia present (Th0)	0.0544	-0.0298	0.1924	0.0393

Annual precipitation was also an important splitting variable occurring three times in the models and indicating higher infestations of ragweed in areas with high annual precipitation. Three further variables emerged as important factors in the models: mean annual temperature and P fertilizer were negatively associated and soil phosphorus concentration positively associated with ragweed abundance (Figs. 3–4).

The calculation of R-squared values and variation partitioning revealed that land-use variables accounted for much more of the variance in the abundance patterns of ragweed than environmental variables. The high adjusted R-squared values indicate that the difference is not due to a higher number of land-use than environmental variables. Dominance of environmental effects is most striking in the field centres, when ragweed cover was >10% (Table 4; Fig. 5).

Discussion

Historical context of the different frequencies recorded along the border

As already mentioned in the introduction, there are very different accounts of the history of the invasion by the common ragweed in the Austrian and the Hungarian scientific literature. To summarize simply, researchers in both countries were aware that ragweed was present and causing problems in their own country, but due to the lack of access to relevant sources they assumed that the presence of this species in the other country is a more recent phenomenon and due to recent political, social and economic changes (Kiss & Béres 2006, Essl et al. 2009, Novák et al. 2011, Mang et al. 2018). This obviously cannot be true, and we hope that this paper will help in disentangling this situation.

Regarding the presence/absence of ragweed in the two countries (Th0), it is remarkable that *A. artemisiifolia* occurred significantly more frequently in Hungary, both at the edges and in the centres of fields. This indicates a longer history of infestations of ragweed in Hungary, with more stable soil seed banks and local populations. One possible explanation is the Hungarian account of high local infestation occurring in the collective agriculture in all Transdanubia, including the regions adjacent to Austria (Fenesi & Botta-Dukát 2011, Novák et al. 2011). This high level of infestation was thought not to extend beyond the border because of the Iron Curtain, which was as an efficient barrier to the spread and so prevented populations in Austria reaching saturation levels. In addition, the very different farming practices (small holdings versus large-scale co-operative farms) also probably helped prevent ragweed crossing the border.

It is notable, however, that the incidence of fields with a relatively high cover of ragweed (Th5, Th10) are similar in the two countries and fields with cover values > 10% (Th10) are even slightly more common in Austria. This indicates that once ragweed becomes established in a field, it can reach similar abundances on both sides of the border. Farmers cannot eradicate common ragweed, but they can reduce its abundance considerably. Today, Hungarian farmers are more likely to prevent ragweed reaching high levels of infestation, because since 2007 the authorities can impose financial penalties for infested fields (Kazinczi et al. 2008b). In Austria there are no similar sanctions in force and this might account for the slightly higher proportion of heavily infested fields recorded there and the high risk of this weed spreading further in the future.

Because of its key importance in determining the spread of ragweed, it is also interesting to look at the differences in land-use systems in the two countries from a historical perspective. According to the Hungarian account in the area studied in Hungary (as well as most of north-western Hungary) *A. artemisiifolia* became established in agricultural fields between 1966 and 1977 (Fenesi & Botta-Dukát 2011). At this time socialist-type large-scale agriculture prevailed in Hungary and the long-distance dispersal of this weed was probably facilitated by the transport over long distances of agricultural produce and the dissemination of seed by agricultural machinery both within and between the large cooperative farms. The dramatic changes in farming practices during the post-communist period after 1990 further contributed to the increase in the size of ragweed populations in Hungary (Kiss & Béres 2006, Novák et al. 2011). This was followed by a gradual opening up of the state border, which eventually led to a very permeable green border with a high number of local crossings between neighbouring settlements after Hungary's accession to the EU (2004) and the Schengen treaty (2007). Traffic and transportation has also increased within both of these countries and also between them, which could provide further corridors facilitating the spread of ragweed (Joly et al. 2011, Lemke et al. 2019).

The role of cross-border transport in the rapid spread of *A. artemisiifolia* is still unknown, and the results presented neither prove nor falsify the various hypotheses. Nevertheless, there are several aspects of the recent history of the two countries that might suggest a significant cross-border transport of propagules. After the regime change but, in particular, following Hungary joining the EU, many Austrian farmers took the opportunity to expand their farm holdings towards the east and invested in arable fields in adjacent regions in Hungary. Their regular commutes with farm machinery most likely resulted in the transport of weed propagules across the border. In this study, 8.3% of the Austrian farmers interviewed owned arable land in Hungary. Karrer (2014) also highlights the great importance of contaminated farm machinery, especially harvesters, in the dispersal of ragweed from field to field in eastern Austria. Similarly, according to Buttenschøn et al. (2009) the renting of combine harvesters was responsible for the introduction of *A. artemisiifolia* from France into some uninfested areas in Switzerland. Interestingly, the rapid spread of *A. artemisiifolia* along major roads in the Austrian lowlands began after 1995 (Essl et al. 2009), when the collapse of the Iron Curtain could also have started to take effect. Nevertheless, the opening of the border is not the only factor behind the spread of common ragweed, as several other socioeconomic changes occurred approximately at the same time, even in the seemingly "unchanged" Austria (Kiss & Béres 2006) and the effect of climate warming should also be considered (Mang et al. 2018). These factors might also have influenced the spread of ragweed. Road networks, for example, have become denser and internal traffic and transportation have also increased in the whole of central Europe (Milakovic et al. 2014, Essl et al. 2015, Hrabovský et al. 2016, Skálová et al. 2017). Thus, *A. artemisiifolia* might also have spread rapidly along the highways connecting the highly infested Austrian lowlands with the area studied, especially routes A2 and A4. However, the role of the various factors, including the border in the spread of ragweed can only be determined by detailed genetic investigations.

The results presented also indicate that in Austria the invasion of *A. artemisiifolia* might still be in progress of saturation in the Austrian borderland. If we accept that the scientists in both countries described the situation correctly with respect to their own country (while making erroneous assumption with respect to the other country), then it is possible there is a 'saturation lag' between the two countries, which can be as much as 20–30 years. The current differences in ragweed occurrences might be seen as legacies of this saturation lag, originally due to the Iron Curtain. Nevertheless, from an even broader perspective all of the discrepancies in the data and literature accessibility resulting in the different accounts of the invasion might be seen as legacies of the Iron Curtain: legacies that had a long lasting effect on the work of the scientific communities.

Predictors of the differences between the countries

Our search for country-dependent factors associated with the different patterns in the ragweed infestation found that the preceding crop could be important. Regarding this variable, mixed trends were identified, but in both models maize and soya bean as previous crops were associated with the high infestations in the centres of Austrian fields. Interestingly, the comparison of the mean cover values of common ragweed in the four crops studied in the two countries revealed they were larger in Austria than in Hungary in maize and soya bean (data not shown). This indicates that the management of common ragweed in these crops is more important for Austrian farmers, as such populations with their massive seed rain can result in greater infestations in the next crop in the rotation. Alternatively, soil cultivation following the harvest of these crops and before the preparation of the seedbed for the next crop, might contain some specific elements that are more likely to stimulate the germination of common ragweed. Similar hidden intrinsic factors might be the reason why previous crop is a stronger explanatory variable than the actual crop. For instance, the preceding crop may have an allopathic role in reducing the germination of ragweed seed the following year. Furthermore, when the crop is harvested may also affect seed production and thus seedling occurrence the following year. Our earlier studies indicate that in Hungary *A. artemisiifolia* is more abundant in crops of sunflower and oil pumpkin following a cereal crop (Pinke et al. 2013, 2018). Interestingly, these findings are in accordance with the present study as ragweed cover values > 5% (Th5) were greater after cereal crops in the centres of Hungarian fields. This might be due to the common practice of stubble ploughing of cereal fields long after the harvest, during which the ragweed can regrow and replenish its seedbank.

Farming type (conventional vs organic) is associated with country-specific patterns: in organic fields common ragweed occurred significantly more frequently in Hungary with high cover values (Th10). In Austria, organic farming has a long tradition and the area of land organically farmed is six times larger than in Hungary (Willer & Schaack 2015). This is most likely associated with greater expertise and more appropriate non-chemical weed management technologies. Modern approaches to non-chemical weed control can be very efficient (Bond & Grundy 2001, Gallandt 2014), in certain cases even better than an application of herbicide (Albrecht et al. 2016). The application of such techniques can thus explain the lower ragweed abundances in Austrian organically farmed fields compared to those in Hungarian fields. However, Fig. 2B also indicates that conventional management in combination with certain previous crops resulted in the opposite tendency: the proportion of highly infested fields is slightly greater in Austria. Although the model indicates preceding crop is the most influential variable, it is possible that chemical weed management in conventional farming systems is implemented very efficiently by Hungarian farmers.

General predictors for the whole area studied

In this study, crop cover was the most important variable associated with the abundance of *A. artemisiifolia* in the whole area studied. The models predict higher infestations of common ragweed if crop cover was lower than 35–65%. Our earlier investigation reports similar correlations in maize and sunflower crops with around 30% as the 'critical limit' (Pinke et al. 2011). These results indicate that high crop cover can create unfavourable conditions for *A. artemisiifolia*, because it grows best in full sunlight (Essl et al. 2015) and it performs poorly at low light intensities (Montagnani et al. 2017). Crop cover is an indirect cultural variable, which depends on many cultural practices, like seeding rate, row spacing, cultivar and application of fertilizers. By managing these parameters it is possible to grow crops with dense canopies early in the season, which will overcome the emerging weed populations (Blackshaw et al. 2007). Successful weed management can also positively influence crop density, but neither mechanical nor chemical weed control were important in the present study. This could be due to crop cover masking the effect of most of the related management and environmental variables. Thus, field trials or controlled experiments would be more appropriate for management-specific investigations, rather than a broad-scale field survey.

In Hungarian soya bean crops the abundance of *A. artemisiifolia* is unexpectedly negatively associated with row spacing (Pinke et al. 2016), which is also in accordance with the finding of Schmidt & Johnson (2004), who state that neither the biomass nor the seed production of *A. artemisiifolia* is decreased by narrow row spacing in the US. This could be attributed to the fact that close row spacing, which results in early crop canopy closure greatly restricts the use of cultivators for mechanical weed control. In addition, the results of our earlier study indicates that cultivating tillage reduces the abundance of this weed, though only in oil pumpkin crops (Pinke et al. 2018). However, the height of a crop should also be considered when interpreting the effects of crop cover. Although our models have not revealed any crop-species specific correlations in this context, common ragweed can more easily overgrow the dense stands of low growing oil pumpkin and medium-sized soya bean, than the taller sunflower and maize. It should be noted that based on the theories outlined above, inter-seeded cover crops are used in winter wheat stubble in US to suppress common ragweed (Mutch et al. 2003), and innovatively also for assisting turf recruitment along sides of Canadian roads (Bae et al. 2015).

Of the climatic variables mean annual precipitation, which ranged from 600–680 mm, appeared to be important, with high infestations of ragweed in the wettest areas. This is in accordance with the results for the whole of Hungary, where values over 600 mm are associated with more frequent occurrences of ragweed in sunflower, maize and cereal stubble (Pinke et al. 2011), and this species is more abundant in the more humid regions in soya bean and oil pumpkin crops (Pinke et al. 2016, 2018). In the present study, mean annual temperature was less important, but was associated with high abundances of ragweed in regions where the mean was under 9.9 °C. In terms of temperature, this weed in sunflower fields in Hungary is most abundant in the cooler regions (Pinke et al. 2013) and in maize and cereal stubble in regions where temperature in May is lowest (Pinke et al. 2011). In conclusion, on the Pannonian Plain as a whole and at its western periphery, the abundance of *A. artemisiifolia* is associated with high precipitation and cool temperatures. Nevertheless, north and west of this region, low temperature is its main environmental constraint

(Skálová et al. 2017, Mang et al. 2018) and in regions close to the Mediterranean it is drought (Chauvel et al. 2006, Chapman et al. 2014, Storkey et al. 2014). A recent European study revealed that plants of *A. artemisiifolia* are bigger in warm and wet areas (Lommen et al. 2018). We also found that the three seasonal temperatures selected were not important predictors of the abundance of *A. artemisiifolia* as the annual climate. The reason for this may be twofold. Other than the fact that seasonal temperatures are correlated with the mean annual temperature, which may mask their effect, they may not be good proxies for the effective climatic factors (i.e. extreme temperatures and drought), that can directly reduce the vigour of ragweed in this region.

It may seem contradictory that the application of P fertilizer was negatively, while soil phosphorus concentration (P_2O_5 indicates the availability of P for plants) was positively associated with the abundance of ragweed. The great amounts of P fertilizer used in the whole area (and also N fertilizers in Austria) probably affect ragweed cover negatively via its stimulating effect on crop cover, which enhances a crop's ability to out compete weeds. This is also supported by the positive correlation between crop cover and application of P (as well as N) fertilizer in our dataset (Electronic Appendix 1). Although several relationships between certain soil properties and the abundance of ragweed are reported in previous studies (Pinke et al. 2011, 2013, 2016, 2018) and similar correlations reported by other authors (Hui-na et al. 2014, Onen et al. 2017, Gentili et al. 2018), the importance of P reported here is a new finding. In our dataset the P content of the soil was not correlated with the other factors. One possible explanation is in the publication of Drake & Steckel (1955), who characterized ragweed as having high cation exchange root systems, which enable this plant to obtain phosphorus from soil more efficiently than other species. Furthermore, mycorrhizal symbiosis can also promote its uptake of P from soil (Koide & Li 1991).

A high soil sodium content is significantly associated with the low incidence of common ragweed at the edges of field in Hungary (Pinke et al. 2011). Onen et al. (2017) also indicate that ragweed is sensitive to salinity, because Na usually decreases the uptake of other essential minerals in this and many other species of plants. The fact that country was recorded as an important splitting variable only once indicates that most of the land-use operations and environmental constraints affected the abundance of ragweed independently of the country (but see the previous section).

Land-use versus environmental factors

Variation partitioning revealed that in the area studied land-use factors are better predictors of ragweed infestations than environmental variables. While the proportion of differences between the two groups of factors are roughly the same for the four threshold limits at the edges of fields, the greater cover values are associated with the greater effect of land-use in the centres of fields. This is in accordance with our earlier findings that the effect of crop management regularly increases from the edge towards the centre of fields (Pinke et al. 2012). Our results also highlight that the build-up of ragweed populations in the centres of fields could be the consequence of improper land use, rather than abiotic constraints.

These finding are not completely in accordance with those of our earlier studies, where in sunflower, soya bean and oil pumpkin fields environmental factors were more important than management in determining the species composition of the weeds (Pinke et al. 2013, 2016, 2018). Nevertheless, there are many other species with different ecological demands recorded in country-wide surveys, which could increase the importance of environmental factors. In the present study, we focused on a single species along moderately long ecological gradient, but given that the study was carried out in two countries, the difference in management is actually larger. Thus, our results indicate that common ragweed has a generalist ecological strategy and its colonization of crops is largely unaffected by environmental variables, but is very susceptible to land-use operations.

Conclusions

The scientific communities in the two countries have produced very different reconstructions of the ragweed invasion. This can probably be seen as a legacy of the Iron Curtain fragmenting scientific communities and limiting mutual access to data and information. Our results are in accordance with the findings of Essl et al. (2011) that current ragweed infestation patterns can partly be explained by historical activities. The common public opinion that the borderline would constitute a sharp boundary in ragweed abundance might have been true between the 1970s and the turn of the millennium. This situation has changed by the gradual dismantling of the closed frontier (from the Iron Curtain of 1989 to a permeable Schengen borderline in 2008). Currently a saturation process may be affecting ragweed colonization of agricultural fields on both sides of the border. This process seems to be in different phases in the two countries, with Austria lagging behind by ~20–30 years (but rapidly catching up). Nevertheless, both ragweed ecology and the physical and socioeconomic factors affecting ragweed populations are now similar in eastern Austria and western Hungary, which will eventually lead to similarly thriving ragweed populations on both sides of the border, unless this is prevented by appropriate weed control measures. This study revealed the substantial role of land-use factors (farming type, crop cover, preceding crop and fertilizer use) in determining the abundance of ragweed, which could be very important in terms of predicting the future spread of this species, as most predictions are based only on climatic variables. This information can also be very useful for planning control measures.

See www.preslia.cz for Electronic Appendix 1

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Souhrn

Karpatská pánev je jedním z nejdůležitějších regionů z hlediska invaze *Ambrosia artemisiifolia* v Evropě. Historie invaze tohoto druhu však byla hodnocena odlišně v Rakousku a Maďarsku; v každé z těchto zemí se předpokládalo, že se zde stal hojnějším a začal působit problémy dříve než v zemi druhé. Cílem této studie je vyjasnit historické nepřesnosti pomocí analýzy současného výskytu ambrózie v plodinách v pohraničních oblastech ve východním Rakousku a západním Maďarsku. Abundance *A. artemisiifolia* byla zaznamenána na 200 polích spolu s informacemi o 31 faktorech prostředí. *Ambrosia artemisiifolia* se vyskytovala častěji v Maďarsku, ale počet ploch s vyšší pokryvností se v obou zemích nelišil a hodnoty pokryvnosti přesahující 10 % byly v Rakousku dokonce o něco častější. V Rakousku se druh častěji vyskytoval na polích s tradičním zemědělstvím, kde se předtím pěstovala kukuřice a sója, zatímco na maďarských polích byla vyšší četnost intenzivního zaplevelení spojena s ekologickým způsobem hospodaření. V celkové analýze byla pokryvnost plodiny nejdůležitější proměnnou, nízká pokryvnost byla spojena s velkou abundancí ambrózie. Teplota a hnojení fosfáty ovlivňovaly výskyt *A. artemisiifolia* negativně, zatímco srážky a koncentrace fosforu v půdě měly pozitivní vliv na její abundanci. Proměnné spojené se způsobem využívání krajiny měly silnější vliv na výskyt ambrózie než ostatní proměnné prostředí. Současné rozšíření ambrózie a jeho příčiny naznačují, že na rakouské straně stále probíhá proces obsazování vhodných stanovišť a s ním spojené dosycování populacemi ambrózie. Zpoždění o 20–30 let oproti Maďarsku je pravděpodobně způsobeno kombinací různých faktorů, přičemž důležitou roli v přeshraniční výměně diaspor hrála zřejmě existence „železné opony“. Rozdíly odhalené v zaznamenávání invaze maďarskými a rakouskými autory však lze též považovat za odkaz „železné opony“, způsobující omezením přístupu k národním údajům a literatuře druhé země v období rychlého šíření ambrózie.

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