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Robinia pseudoacacia-dominated vegetation types of Southern Europe: Species composition, history, distribution and management

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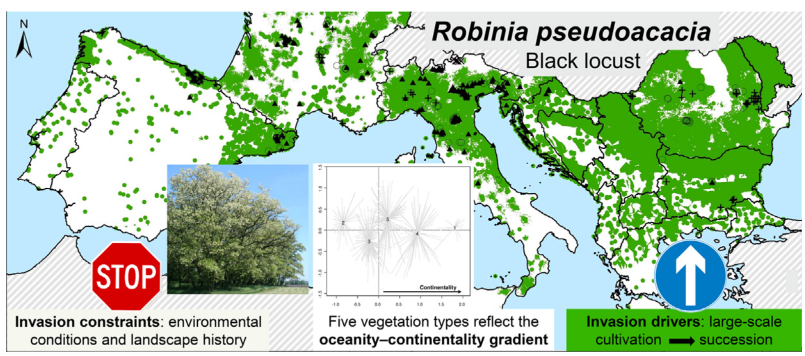
HIGHLIGHTS

- Five vegetation types reflect an oceanity-continentality gradient in South Europe.
- *Robinia* stands have specific species composition and high structural diversity.
- The main drivers of invasion is large-scale and long-term cultivation.
- The most invaded habitats are human-made, e.g. urban, agrarian and mining areas.
- Stratified management on regional and local scales should be favoured.

GRAPHICAL ABSTRACT



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ABSTRACT

Knowledge of the species composition of invaded vegetation helps to evaluate an ecological impact of aliens and design an optimal management strategy. We link a new vegetation analysis of a large dataset to the invasion history, ecology and management of *Robinia pseudoacacia* stands across Southern Europe and provide a map illustrating *Robinia* distribution. Finally, we compare detected relationships with Central Europe.

We show that regional differences in *Robinia* invasion, distribution, habitats and management are driven both by local natural conditions (climate and soil properties, low competitive ability with native trees) and socioeconomic factors (traditional land-use). Based on the classification of 467 phytosociological relevés we distinguished five broad vegetation types reflecting an oceanity−continentality gradient. The stands were heterogeneous and included 824 taxa, with only 5.8% occurring in more than 10% of samples, representing mainly hemerobic generalists of mesophilous, nutrient-rich and semi-shady habitats. The most common were dry ruderal stands invading human-made habitats. Among native communities, disturbed mesic and alluvial forests were often invaded throughout the area, while dry forests and scrub dominated in Balkan countries. Continuous, long-term and large-scale cultivation represent a crucial factor driving *Robinia* invasions in natural habitats. Its invasion should be mitigated by suitable

Abbreviations: Robinia, *Robinia pseudoacacia*; CE, Central Europe; SE, Southern Europe.

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management taking into account adjacent habitats and changing cultivation practices to select for native species. *Robinia* invasion has a comparable pattern in Central and Southern Europe, but there is a substantial difference in management and utilization causing heterogeneity of many South-European stands.

1. Introduction

Black locust, *Robinia pseudoacacia* L.,is a widely distributed temperate tree species, considered as both ecologically risky and economically beneficial in many countries (Vítková et al., 2017). *Robinia* is expansive in its native range (Shure et al., 2006) and invasive in many regions where it has been introduced (e.g. Richardson and Rejmánek, 2011; Rumlerová et al., 2016; Roy et al. 2019; https://www.cal-ipc.org). It is a typical ecosystem transformer (sensu Richardson et al., 2000) and a fast growing colonizer (e.g. Rédei et al., 2014) which outcompetes other plants, thus reducing local biodiversity (e.g. Benesperi et al., 2012; Nascimbene et al., 2012; Sitzia et al., 2012). Furthermore it shows a homogenizing effect on species composition of both tree and herb layers (e.g. Trentanovi et al., 2013; Šibíková et al., 2019) and changes the community in favour of ruderals, aliens and generalists at the expense of native species and habitat specialists (e.g. Nascimbene and Marini, 2010; Reif et al., 2016; Sitzia et al., 2018). These changes are caused by its ability of nitrogen fixation (e.g. Du et al., 2019) and its impact on light regime and soil environment including soil biota (Lazzaro et al., 2018), decomposition rate (e.g. Castro-Díez et al., 2012) and nutrient availability (e.g. Montagnini et al., 1991; Vítková et al., 2015). In specific cases (Vítková et al., 2017), *Robinia* has some positive effects on the species diversity of other trophic levels, such as birds (Reif et al., 2016), invertebrates (Kowarik, 1994) and macrofungi (Ślusarczyk, 2012), as well as on some functional groups of plants, such as geophytes (Vítková and Kolbek, 2010).

Robinia has been long cultivated for multiple purposes (e.g. timber and energy production, amelioration, reclamation of disturbed sites, honey production, forage and for ornamental reasons; Iliev et al., 2005; Yüksek, 2012; Nicolescu et al., 2018). The species spreads rapidly by root suckers (e.g. Kowarik, 1996), however, its ability of long-distance dispersal as well as the establishment of new populations is rather low (Pyšek et al., 2012b). The current abundance of *Robinia* in Europe results from its deliberate cultivation in open landscapes and large-scale afforestation campaigns, followed by spontaneous spread (Vítková et al., 2017; Sádlo et al., 2017). It was recognized as noxious invader in the first half of the 20th century (Vadas, 1914; Wendelberger, 1954), and this view was widely accepted later, regardless of the landscape context (Vítková et al., 2017). The species ranks 13th amongst the most invasive alien species in Europe and has the fifth strongest environmental impact (Nentwig et al., 2018). *Robinia* is not included in the list of invasive alien species of European Union concern adopted on the basis of the Regulation (EU) 2016/114. However, it meets the definition of "a widely spread invasive alien species" provided by Art. 3 of the same Regulation and, pursuant to its Art. 12, it may be listed in national lists of Member State's concern (Sitzia et al., 2016b). *Robinia* is also listed as invasive by some national legislations, for example in Portugal, where its cultivation is forbidden even for ornamental purposes (Decree-Law, 1999/565). Some regional rural development programs provide incentives for its eradication and do not support projects involving *Robinia* cultivations.

According to Sitzia et al. (2016a), the core area of *Robinia* distribution in Europe lies in sub-Mediterranean to warm continental climates. The spread of the species is allowed by radical changes in the landscape caused by extensive urban development, horticultural boom and the conversion of degraded pastures and abandoned agricultural lands to forests (e.g. BOEP, 2013; Enescu and Dănescu, 2013; Campagnaro et al., 2018a). These processes support the introduction of new cultivars of *Robinia* as well as intentional cultivation which results in spontaneous invasion. However, knowledge about *Robinia* distribution, habitat conditions and invasion history in individual SE countries is uneven and scattered across different sources. At the same time, documents covering whole continent, such as DAISIE factsheet (www.europe-aliens.org) or the study of Sitzia et al. (2016a), focus rather on the global patterns than on the variability between the regions.

The main goal of our study was to assess the environmental impact of *Robinia* at local and regional scales in SE and to detect differences compared to CE (according to Vítková et al., 2017). Although understanding the species composition of invaded plant communities enables to evaluate important aspects of the ecological impacts of invasive species (Pyšek et al., 2012a), as well as to establish optimal management strategies that reconcile environmental, cultural and economic priorities (Pergl et al., 2016; Vítková et al., 2016, 2017, 2018), published floristic records concerning SE *Robinia* stands are rare and unevenly distributed. Their sorting into phytosociological system is also on the edge of SE botanists' interest and therefore often overlooked (Rivas-Martinez et al., 2001), with several exceptions (e.g. Ubaldi, 2013; Allegrezza et al., 2019). Studies dealing with the economic benefits of *Robinia*, such as biomass and wood production (e.g. Grünewald et al., 2009; Nicolescu et al., 2018), tend to reduce the whole forest ecosystem to the silviculture of target tree species whereas other plants in the invaded community are ignored. Therefore, they cannot replace broad-scale vegetation survey because most *Robinia* forests include an admixture of other trees and harbour a developed understorey (Vítková and Kolbek, 2010).

The abovementioned lack of data was the reason for preparing this original comparative and synthetizing study instead of a mere overview. Here, we collected new vegetation, ecological and cultural data which we put together and harmonized with scattered previously known data on *Robinia* in SE to reconcile the attitudes of various disciplines and approaches. Only an understanding of complex relationships in the invaded ecosystem can result in optimal management strategy that will work at the landscape level to control *Robinia* as a threat to valuable native communities.

We defined several basic research questions: (i) Is *Robinia* evenly distributed across SE or are there any environmental barriers for its further invasion? (ii) Which are the main differences between invasion history, ecology and management of this species in different parts of SE and how do they affect its distribution? (iii) Which main plant traits and vegetation types can be defined to characterize *Robinia* stands in SE? (iv) Is there any connection among vegetation composition, ecological and cultural factors? (v) What are the main drivers of *Robinia* invasion in SE? (vi) Are there any substantial differences between SE and CE?

2. Material and methods

2.1. Study area

For the purpose of this study, SE is delimited by 47°N and 30°E, including Albania, Bosnia and Herzegovina, Bulgaria, Croatia, southern parts of France, Greece, Italy, Kosovo, Macedonia, Moldova, Montenegro, Portugal, Romania, Serbia, Slovenia, Spain, and European parts of Turkey (Fig. 1). Small territorial units such as Andorra were not considered. Border countries such as Austria, Switzerland, and Hungary were included as part of CE and analysed in previous studies (Vítková and Kolbek, 2010; Vítková et al., 2017). The concept of bioclimatic zones follows Rivas-Martínez et al. (2011). We chose CE as a comparative region because *Robinia* is common there and has a long tradition of multi-faceted research (e.g. Vadas, 1914; Kowarik, 1994; Vítková and Kolbek, 2010; Vítková et al., 2015, 2017; Sádlo et al., 2017).

2.2. Environmental data

Data on the history of cultivation, invasiveness, invaded habitats and management are original reports obtained using inquiries addressing relevant regional experts in nature conservation, invasion ecology and forestry (Table A1). To exclude the subjectivity of respondents and to get a comparable dataset across SE, we standardized questionnaire data using information from grey literature mentioned below the Table A2, our field experience and Google Street View that provided additional data on structure of *Robinia* stands growing along roads (Deus et al., 2016).

By considering origin, structure, species composition and invaded habitats, we applied a simplified classification of Sádlo et al. (2017) for a description of management types.

2.3. Phytosociological data

Initially, we collected 5,217 phytosociological vegetation plot records (relevés) with the presence of *Robinia* from (i) European Vegetation Archive (EVA; 4,931 relevés; Chytrý et al., 2016), (ii) local grey literature (269 relevés from 15 papers), and (iii) unpublished field research (17 relevés from Bulgaria) (Table 1). These relevés were sampled using the Zürich-Montpellier approach (Dierschke, 1994), mostly with Braun-Blanquet scale of cover-abundance estimates for each species (Dengler et al., 2008). The relevés were stored in Turboveg for Windows 2.92 database (Hennekens and Schaminée, 2001) and processed in Juice 7.0 software (Tichý, 2002). Relevés lacking geographical coordinates were georeferenced using the Google Earth® program (www.google.com/earth, Google Inc., Mountain View, CA, USA). All relevés north of the 47th parallel, as well as relevés without sufficient information on geographical location were excluded. Since we wanted to assess the impact of canopy dominated by *Robinia* on vegetation composition, we excluded also the relevés with its cover below 38% (i.e. less than grade 3 on the Braun-Blanquet scale). This condition was met by 574 relevés. To handle oversampling in some areas (e.g. Italy, see Table 1), we performed heterogeneity-constrained resampling so that a maximum 3–7 relevés, depending on beta-diversity per 1.5 × 1.5 km quadrat, were retained (Lengyel et al., 2011). The resulting dataset included 467 relevés. All vegetation layers (tree, shrub, herb, and seedling) were combined into a single layer (half of the data included a single layer already in the original sources). As bryophytes and lichens were not recorded in the majority of plots, they were excluded from the dataset.

The plant names follow The Plant List (2013). To unify taxonomic concepts used in different countries and by different authors, some taxa were merged to a higher taxonomic level (see Table A3).

2.4. Distribution map

We created a map approaching the current distribution of *Robinia* in SE, including both intentionally planted and spontaneously spreading *Robinia* stands on forest and non-forest land (Fig. 1). We distinguished areas with the common occurrence of *Robinia*, i.e. where the species often forms invasive populations with the assumption for further spread. In the remaining areas, *Robinia* does

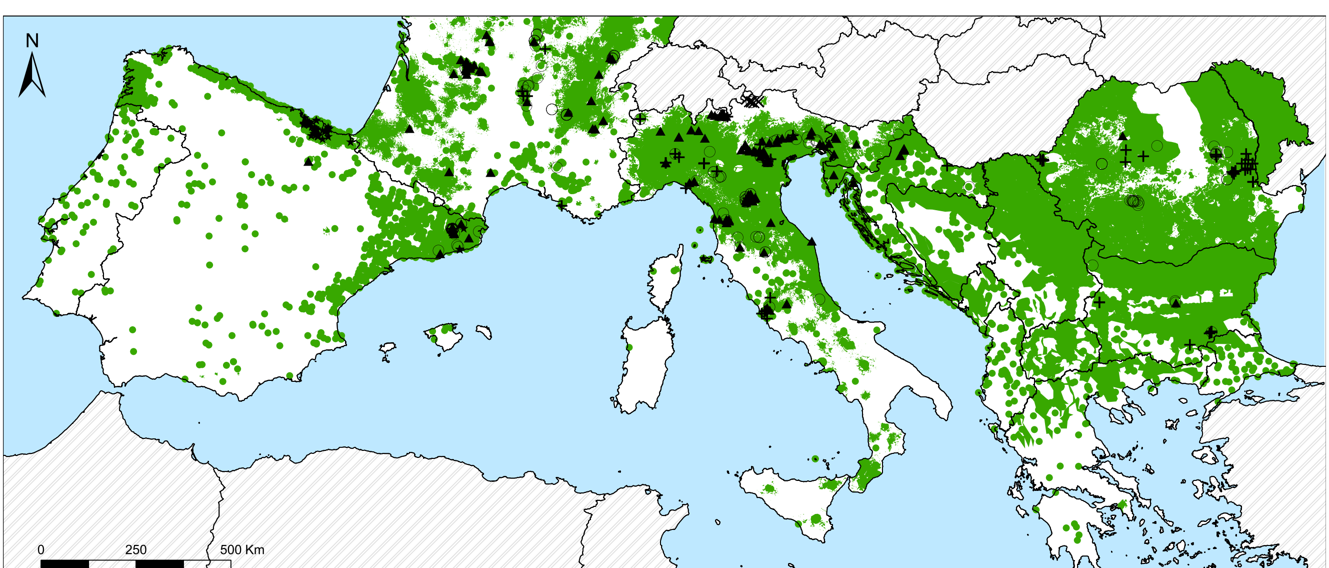

Fig. 1. Distribution map of *Robinia pseudoacacia* in Southern Europe which was compiled from several sources listed in Table A4 and Fig. A2 according to the decision tree in Fig. A1. Areas where the species frequently occurs and often forms invasive populations with assumed further spread are marked in grey (in the web version in green). Areas with none or rare occurrence in small populations, seldom able to invade are marked in white. Phytosociological relevés are divided according to numerical classification into five vegetation types – 1 (i.e. X) Open stands with dry-grassland species; 2 (i.e. star) Stands of precipitation-rich areas; 3 (i.e. triangle) Stands of mesic woodland areas, 4 (i.e. cross) Dry ruderal stands; and 5 (i.e. circle) Mesic nitrophilous stands. For a detailed explanation see Fig. 3.

Table 1
The list of sources of phytosociological relevés with *Robinia pseudoacacia* in Southern Europe.

Country	References	GIVD (Global Index of Vegetation-Plot Databases)			Nr. of relevés	
		Name of Databases	ID	Main custodian(s)	*Robinia* occurrence	*Robinia* cover greater than 30%
Albania	-	Vegetation Database of Albania	EU-AL-001	De Sanctis	1	0
Bosnia and Herzegovina	–	SE Europe Forest Database; Croatian Vegetation Database	EU-00-021; EU-HR-002	Carni; Škvorc	3	0
Bulgaria	Mucina & Kolbek (1989), Balazs (2008), Sádlo (unpublished)	Balkan Dry Grassland Database; Balkan Vegetation Database; Bulgarian Vegetation Database; Gravel Bar Vegetation Database; European Coastal Vegetation Database; Mediterranean Ammophiletea Database	EU-00-013; EU-00-019; EU-BG-001; EU-00-025; EU-00-017; EU-00-016	Vassilev; Apostolova; Kalníková; Janssen; Marcenò	258	22
Croatia	–	Croatian Vegetation Database; SE Europe Forest DB	EU-HR-002; EU-00-021	Škvorc; Carni	228	8
France	Remon (2006)	SOPHY; Swiss Forest Vegetation Database; Iberian and Macaronesian Vegetation Information System (SIVIM); Iberian and Macaronesian Vegetation Information System (SIVIM) – Deciduous Forests; EcoPlant	EU-FR-003; EU-CH-005; EU-00-004; EU-00-023; EU-FR-005	Garbolino; Wohlgemuth; Font Castell; Campos; Gegout	2,133	74
Greece	–	Kriti; Greek Woodland Vegetation Database; Hellenic Natura 2000 Vegetation Database	EU-GR-001; EU-GR-002; EU-GR-005	Bergmeier; Dimopoulos	66	0
Kosovo	–	–	–	–	–	–
Italy	Buffa & Ghirelli (1993); Gentile (1995); Arrigoni (1997); Fizitea (1999); Parolo (2000); Andreucci et al. (2003); Arrigoni & Papini (2003); Ubaldi (2003); Poldini & Vidali (1995); Wilhalm et al. (2008); Campagnaro et al. (2018b)	SOPHY; Swiss Forest Vegetation Database; SE Europe Forest Database; Gravel Bar Vegetation Database; Italian National Vegetation Database; Vegetation Plot Database - Sapienza University of Rome; VegItaly; Mediterranean Ammophiletea Database	EU-FR-003; EU-CH-005; EU-00-021; EU-00-025; EU-IT-010; EU-IT-011; EU-IT-001; EU-00-016	Garbolino; Wohlgemuth; Carni; Kalníková; Agrillo; Casella; Venanzoni; Marcenò	930	207
Macedonia	–	Gravel Bar Vegetation Database	EU-00-025	Kalníková	1	0
Moldova	–	–	–	–	0	0
Montenegro	–	Croatian Vegetation Database	EU-HR-002	Škvorc	1	0
Portugal	–	Iberian and Macaronesian Vegetation Information System (SIVIM) – Floodplain Forests	EU-00-024	Biurrun	23	0
Romania	Oprea (2004); Niculescu et al. (2010, 2014)	Romanian Forest Database; Romania Grassland Database; Mediterranean Ammophiletea Database; Balkan Dry Grassland Database; Gravel Bar Vegetation Database; European Coastal Vegetation Database	EU-RO-007; EU-RO-008; EU-00-016; EU-00-013; EU-00-025; EU-00-017	Indreica; Ruprecht; Marcenò; Vassilev; Kalníková; Janssen	325	64
Serbia	–	Balkan Dry Grassland Database; Database of Forest Vegetation in Republic of Serbia; Vegetation Database of Northern Part of Serbia; Croatian Vegetation Database; Vegetation Database Grassland Vegetation of Serbia; Balkan Vegetation Database; SE Europe Forest Database; Gravel Bar Vegetation Database; WetVegEurope	EU-00-013; EU-RS-003; EU-RS-004; EU-HR-002; EU-RS-002; EU-00-019; EU-00-021; EU-00-025; EU-00-020	Vassilev; Ćuk; Škvorc; Aćić; Carni; Kalníková; Landucci	246	0
Slovenia	–	Vegetation Database of Slovenia; SE Europe Forest Database; SOPHY	EU-SI-001; EU-00-021; EU-FR-003	Šilc; Carni; Garbolino	342	0
Spain	–	Vegetation-Plot Database of the University of the Basque Country (BIOVEG); SOPHY; Iberian and Macaronesian Vegetation Information System (SIVIM) – Deciduous Forests; Iberian and Macaronesian Vegetation Information System (SIVIM) – Wetlands; Iberian and Macaronesian Vegetation Information System (SIVIM) – Floodplain Forests	EU-00-011; EU-FR-003; EU-00-023; EU-ES-001; EU-00-024	Biurrun; Garbolino; Campos; Pérez-Haase	422	92
Turkey	–	Vegetation Database of the Grassland Communities in Anatolia	AS-TR-001	Ugurlu	238	0
Total Nr of Relevés					**5,217**	**467**

not grow at all or only rarely, in small populations and seldom able to invade.

Because there is no consistent mapping approach available for *Robinia* distribution across SE countries, we combined a variety of sources differing in mapping methods (Table A4). They represented three categories: (i) real distribution – localities of phytosociological relevés with *Robinia* presence (see section 2.3), regional maps with current distribution (forest maps, citizen science maps, floristic inventories); (ii) modelled distribution (i.e. the model of the relative probability of presence of *Robinia* in Europe, with more than 30% probability of *Robinia* included; De Rigo et al., 2016; Sitzia et al., 2016a) based on extant data (e.g. field observations of European National Forest Inventories), and (iii) incomplete or missing distribution data. The process of creating our distribution map of *Robinia* from these heterogeneous sources is shown in Fig. A1. Fig. A2 shows existing localities of *Robinia* in SE which were used as sources for the map.

The model distribution was used as a basis for the map only in France, Italy, Romania, and partly in Bulgaria and Serbia, whereas in other regions the model either underestimated or overestimated the real distribution of the species and most of Iberian and Balkan Peninsulas does not even include *Robinia* at all. For example, areas with a high presence of *Robinia* were mapped in high mountains of north-western Bulgaria, actually covered by dense coniferous forests and subalpine pastures where *Robinia* is not able to grow (Vítková et al., 2017). Therefore, in Portugal, Spain, Albania and Croatia, we replaced the model by regional maps of current *Robinia* distribution. In Bosnia and Herzegovina, Greece, Kosovo, Macedonia, Moldova, Montenegro, Turkey, and locally in Bulgaria and Romania, there were either incomplete or missing distribution data, therefore we created new local maps based on large-scale landscape characteristics which were detected as limiting *Robinia* occurrence across SE (see section 3.2 and Fig. A1).

In the next step, we harmonized the sources of the map and compared them with results of our field research, local maps of climate, land cover and land use (e.g. WorldClim database, Hijmans et al., 2005; Corine Land Cover map, CLC2012, Büttner, 2014). Furthermore, we performed Google Street View verification using ~ 9,000 random points or 360° photos in the eastern part of SE (i.e. from Croatia to Turkey), and ~ 3,000 points in the western part (i.e. from Portugal to Slovenia). We detected that abundance of *Robinia* along roads is a suitable indicator of its broad distribution in the adjacent landscape. We tested this verification method on 40 transects each ~ 20 km long, with ~ 1-km sampling interval, leading through the landscape with the known distribution of *Robinia* (Table A5).

2.5. Classification of vegetation types

Given that the resampled dataset was much smaller than the original one (i.e. 467 vs. 5,217 relevés), we tested its robustness using modified Twinspan classification (Roleček et al., 2009) and the analysis of diagnostic, constant and dominant species using the Juice 7.0 program (Tichý, 2002). Species with a frequency under 5% were excluded to reduce noise prior to classification (Tsiripidis et al., 2007). Because the results were robust, we used the reduced dataset and in the next step we compared its classification using several frequently applied algorithms: modified Twinspan, beta-flexible, Ward's method (Podani, 2001), K-means (Tichý et al., 2014) and Isopam (Schmidtlein et al., 2010) clustering into different numbers of clusters. Based on the analysis of diagnostic, constant and dominant species we identified three former algorithms which provided similar groups. Crispness analysis (Botta-Dukát et al., 2005) showed the highest support for classification into five groups. We chose modified Twinspan algorithm for final classification so that the resulting vegetation types reflect the main gradients in species composition (Roleček et al., 2009). Vegetation types are presented using a synoptic table with diagnostic species shown. Species with *phi* coefficient values (×100) higher than 20 and significantly related to a vegetation type (Fischer's exact test level $\alpha = 0.01$) were considered diagnostic (see Table 3).

Classification results were projected on the ordination space of Detrended Correspondence Analysis (DCA) using the "vegan" library (Oksanen et al., 2015, version 2.0–10) in R program (R Core Team 2016, version 2.9.1) operated from Juice. Before analysis, logarithmic transformation of percentage covers and downweighting of rare species using the vegan package defaults based on the original Decorana code (Hill and Gauch, 1980) were performed. To assist ecological interpretation of the compositional gradients, we projected basic geographical and bioclimatic variables to the ordination space. We only included those variables that explained a significant portion of variation in species composition in Canonical Correspondence Analysis (CCA). Canoco 5 software (Šmilauer and Lepš, 2014) was used for testing (Monte Carlo permutation test with $\alpha = 0.05$). Bioclimatic variables were retrieved from the WorldClim database (Hijmans et al., 2005). Each vegetation type was named according to the most important ecological gradient and/or habitat characteristic.

2.6. Evaluation of plant traits

Each taxon was classified according to (i) life form (i.e. 1. trees, 2. erect shrubs, 3. climbing shrubs and perennials, 4. erect perennials, and 5. annuals and biennials), (ii) habitat associations (i.e. 1. high light and low nutrient conditions, 2. mesic habitats with moderate light, moisture, and nutrient conditions, 3. shady forests and scrub, and 4. ruderal nitrophilous species), and (iii) sensitivity to human influence (i.e. 1. indicator of naturalness, 2. indicator of hemeroby, 3. alien status, at least in some countries). These data were adopted in simplified form from Pladias database containing life form (Klimešová et al., 2017), habitat demands (Chytrý et al., 2018) and sensitivity to human influence (Klotz and Kühn, 2002). Traits of several species not included in Pladias were compiled from respective local floras (e.g. Hegi, 1975). The classified characteristics of the species were displayed using bar charts based on average percentage frequencies (Fig. 2).

2.7. Evaluation of invasion drivers

Based on inquiries of regional experts (Table A1), we determined invasion drivers which were used as predictors. The relations between these predictors and the performance of *Robinia* in the individual SE countries was tested using the non-parametric ANOVAs, as the response variables (area of *Robinia* forests; the species' residence time; time since the first wave of afforestation according to Table 2) revealed significant deviations from normality, even after transformations. This was very likely caused by the severe outlier values in the response data. To test the relations between invasion drivers and area occupied by *Robinia* in individual SE countries we used only data for both planted and spontaneous stands growing on forest land. The area of *Robinia* stands on non-forest land can be large and considerably different among individual SE countries, but its extent is unknown. However according to Křivánek et al. (2006) planting area has a significant effect on the number of localities outside forestry cultivation.

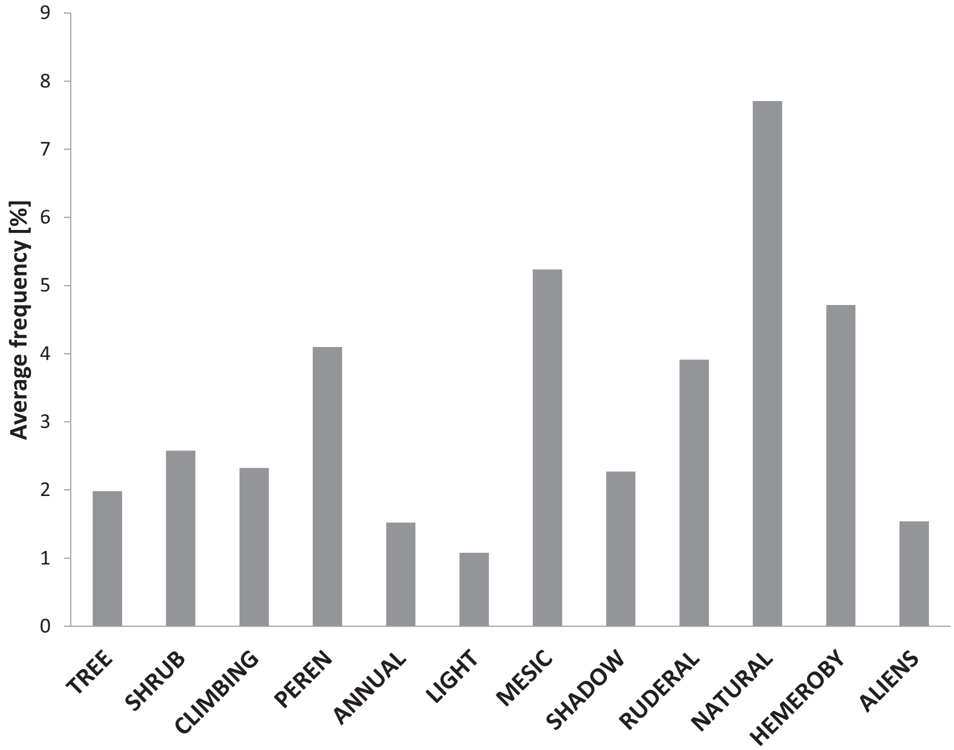

Fig. 2. Comparison of plant traits in *Robinia* stands growing in Southern Europe. Abbreviations: TREE – trees; SHRUB – erect shrubs; CLIMBING – climbing shrubs and perennials; PEREN – erect perennials; ANNUAL – annuals and biennials; LIGHT – high light and low nutrient conditions; MESIC – mesic habitats with moderate light, moisture, and nutrient conditions; SHADOW – shady forests and scrub; RUDERAL – ruderal nitrophilous species; NATURAL – indicator of naturalness; HEMEROBY – indicator of hemeroby; ALIENS – alien status, at least in some countries. See text for details.

Table 2
Distribution and history of *Robinia* cultivation in Southern Europe.

Country	Area of *Robinia* forests (ha)	First record of planting	First wave of afforestation	References
Albania	20,000 (1.3%)	1929–1930	1955	Meta (1993); ANFI (2004); Metaj and Zoto, pers.com.
Bosnia and Herzegovina	15,200 (0.7%)	1880	early 20th century	Maslo (2016); Cvjetković et al. (2017)
Bulgaria	150,590 (4%)	middle of 19th century	end of 19th century	Iliev et al. (2005); Petrova et al. (2013)
Croatia	12,004 (0.05%)	1880	end of 19th century	Perić et al. (2017); Đodan et al. (2018); Đodan and Perić, pers. com.
France (Southern)	64,000 (0.4%)**	after 1650	second half of 19th century	Orazio and Bastien (2017); https://agriculture.gouv.fr
Greece	16,390 (0.4%)*	1835	second half of 19th century	Alizoti (2017); Xanthopoulos, pers. com.
Italy	377,186 (4.3%)	1662	second half of 19th century	Bellucci (1662); Rizzi (1847); Caruel (1867); Monteverdi et al. (2017)
Kosovo	2,400 (0.5%)	no data	not used	Tomter et al. (2013); Maxhuni, pers. com.
Macedonia	2,622 (0.3%)	1873	1914	Andonovski and Mandjukovski (2017); Simovski, pers. com.
Moldova	131,000 (36.1%)	middle of 19th century	1950	Rotaru (2003); Gulca (2009)
Montenegro	715 (0.1%)	1911	not used	Stešević and Petrović (2010); Curovic and Curovic (2017)
Portugal	less than 1,000 (0.03%)	1750–1800 (1804[x])	not used	de Almeida and Freitas (2006); ICNF (2013); Rosa (2013); Tomé et al. (2017)
Romania	250,000 (3.6%)	1750	1852	Călinescu (1941); Haralamb (1967); Palaghianu and Dutca (2017)
Serbia	169,154 (7.5%)	early 19th century	middle of 19th century	Andrašev et al. (2017), Andrašev, pers. com.
Slovenia	157,148 (13.3%)	early 19th century	1858	Anonymous (1858); Rudolf and Brus (2006); Brus et al. (2017)
Spain	2,225 (0.01%)	1752	end of 19th century	Elorza et al. (2004); GEIB (2006); Castro-Diez et al. (2017)
Turkey (European)	20,000 (0.1%)***	1920s	middle of 20th century	Kayacık (1951); Saatçioğlu (1969); Konukçu (2001)

*The cover includes both *Robinia pseudoacacia* and *Acacia* sp.
**Estimated cover based on the total area of *Robinia* in France and its distribution in Southern France
***This value relates to the whole territory of Turkey.
[x]First report of naturalization

Table 3
Diagnostic species combination in vegetation types of South European *Robinia* stands sorted by the highest frequency and fidelity within the each type.

Vegetation type	1	2	3	4	5
Number of relevés	20	62	155	90	140
Diagnostic species combination	*Melica ciliata*	*Rubus ulmifolius* agg.	*Acer campestre*	*Bromus sterilis*	*Rubus caesius*
	Carex liparocarpos	*Polystichum setiferum*	*Rubus fruticosus* agg.	*Elymus repens*	*Humulus lupulus*
	Tragopogon dubius	*Hypericum androsaemum*	*Anemone nemorosa*	*Ballota nigra*	*Urtica dioica*
	Berberis vulgaris	*Holcus mollis*	*Corylus avellana*	*Acer tataricum*	*Bryonia dioica*
	Festuca valesiaca	*Dryopteris filix-mas* agg.	*Prunus avium*	*Hordeum murinum* agg.	*Glechoma hederacea*
	Carex supina	*Athyrium filix-femina*	*Polygonatum multiflorum*	*Achillea setacea*	*Populus nigra* / ×*canadensis*
	Festuca rupicola	*Angelica sylvestris*	*Carpinus betulus*	*Convolvulus arvensis*	*Cornus sanguinea*
	Phleum phleoides	*Agrostis capillaris*	*Quercus petraea*	*Anthriscus cerefolium*	*Alliaria petiolata*
	Centaurea stoebe	*Smilax aspera*	*Fraxinus ornus*	*Conium maculatum*	*Ficaria verna*
	Saponaria ocymoides	*Brachypodium rupestre*	*Pulmonaria officinalis* agg.	*Torilis arvensis* agg.	*Viola hirta* agg.

3. Results

3.1. History of cultivation and invasion

We detected similar course but different timing of *Robinia* introduction, planting and escape in SE countries. The tree was being introduced since the second half of 17th century until 1929; first to France and Italy, followed by Romania, Portugal and Spain in the 18th century, and last to Balkan countries (Table 2). At the beginning, *Robinia* was only used as an ornamental tree in parks and gardens. It probably started to escape shortly after its introduction, which demonstrates the high invasiveness of the species. The lag phase was usually long, and frequent planting in the wild started invasion in the surroundings. For example, in Portugal, *Robinia* was introduced in the second half of the 18th century and its first naturalization was already reported in 1804 (Table 2). Despite its early introduction, *Robinia* still does not form large stands there (Fig. 1), and only occurs as solitary trees or small populations without distinct structure and species composition. The species has never been used for timber production in Portugal, neither in Montenegro and Kosovo, and was only planted on a small scale as a melliferous species, in protective forest belts and linear features along roads, railways, in settlements and disturbed areas (Table 2 and A2). On the other hand, rapid and large invasion occurs in countries where *Robinia* was used repeatedly in large-scale afforestation projects (e.g. Romania and Bulgaria).

3.2. Distribution

There is no available map showing current distribution of *Robinia* in SE, moreover the total cover of the species reported for individual SE countries refers only to forest land (Table 2). However, most *Robinia* populations occur on non-forest land as solitary trees or clusters, groves or shrubberies growing spontaneously (especially in Balkan countries), or established intentionally (e.g. energy plantations) and their location and area remain unknown. Therefore, we created a distribution map (Fig. 1) merging cultural and spontaneous occurrences on forest and non-forest land.

Cover of *Robinia* stands varied considerably among individual countries (Fig. 1, Table 2); from less than 1% of forested area in most countries, between 3.6 and 7.5% in Romania, Bulgaria, Italy, and Serbia to the highest values 13.3% and 36.1% in Slovenia and Moldova. As shown in Fig. 1, we detected black locust landscapes where *Robinia* is forming numerous large stands and colonizing most of the suitable habitats. Such regions have an old tradition of *Robinia* plantings, for example the hilly landscapes bordering the southern Prealps (Italy), river basins of Sava (Croatia, Bosnia and Herzegovina, Serbia) and Olt (Romania), Stara Planina foothills (Serbia and Bulgaria) and large lowland areas in Bulgaria and Moldova.

The distribution and further spread of *Robinia* is restricted by environmental and historical features of the landscape. Based on qualitative expert-based analysis of various sources evaluated for creating the map of *Robinia* occurrence (Fig. 1), we detected the following large-scale constraints reducing its invasion: (i) altitudes over 900 m a.s.l., i.e. mostly covered by mountain forests and at higher altitudes by subalpine to alpine vegetation; (ii) natural areas covered by native trees, sparsely inhabited and mostly situated in mountain hillsides; (iii) zones of hot Mediterranean climate, typically with the occurrence of olives, eucalypts or palms (except big cities such as Istanbul); (iv) large marshland and wetland areas which are not summer-dry, such as Po and Danube river deltas; (v) cool intermontane basins with open cultural landscape and scattered *Alnus* and *Salix* stands on wet soils, for example near Brașov (Romania); and (vi) areas where *Robinia* has never been cultivated on a large scale for historical reasons, such as most parts of Montenegro or Portugal. We summarized abovementioned constraints into four main ecological factors limiting *Robinia* invasion in SE: (i) climate: both cold, combined with a short vegetation season in high altitudes, and hot and dry in southern parts of SE; (ii) soil properties, namely soil hypoxia connected with high soil moisture of long-term waterlogged and compact soils; (iii) low competitive ability with native trees: tree shade in closed forests and shrubland; and (iv) historical land-use.

3.3. Species diversity and composition

Robinia often forms species-rich mixed forests with heterogeneous plant composition; of 824 taxa in phytosociological relevés, only 48 (5.8% of their total number) showed frequencies over 10%, whereas 568 (69%) displayed frequencies below 1%. The following 10 species were most common in the dataset with decreasing frequency from 51 to 31%: *Hedera helix*, *Sambucus nigra*, *Crataegus monogyna*, *Urtica dioica*, *Euonymus europaeus*, *Geum urbanum*, *Galium aparine*, *Clematis vitalba*, *Cornus sanguinea* and *Dioscorea communis.* The most frequent were hemerobic generalists of mesophilous, nutrient-rich and semi-shaded habitats, namely native nemoral perennials (e.g. *Arum maculatum* agg., *Brachypodium sylvaticum*, *Dryopteris filix-mas* agg., *Lamium galeobdolon* and *Viola odorata* agg.) and ruderal species which were perennial (e.g. *Ballota nigra* and *Elymus repens*) or annual (e.g. *Bromus sterilis* and *Geranium robertianum*; Fig. 2). Other life forms were commonly represented by tall shrubs and small trees (i.e. *Acer campestre*, *Corylus avellana*, *Prunus spinosa* and *Ulmus minor*) and herbaceous or woody lianas including climbing shrubs and tall herbs (i.e. *Clematis vitalba*, *Galium aparine*, *Hedera helix*, *Rosa canina* agg. and *Rubus fruticosus* agg.). The number of aliens was rather low.

3.4. Vegetation types

Based on the classification of the dataset, we distinguished five broad vegetation types (see Fig. 1 for geographical distribution and Fig. 3 for spatial arrangement of the clusters in a hierarchical tree) which did not show affinity to any specific management. Each type included *Robinia* plantations, abandoned post-cultural stands and related spontaneous successional stages.

The floristic composition of each type was expressed by species fidelity that was used to compare among the types (Table 3 and Table A6). In the dendrogram (Fig. 3), Cluster 1 (open stands with dry-grassland species) was characterized by very limited distribution, a small number of relevés and high number of species with high fidelity (Fig. 1). The remaining relevés splitted into two groups, each consisting of two clusters. Cluster 2 (stands of precipitation-rich areas) and Cluster 3 (stands of mesic woodland areas) share shady forest species, such as *Polystichum setiferum*. The second pair (i.e. Clusters 4 and 5; dry ruderal stands and mesic nitrophilous stands, respectively) shared widespread ruderal species, such as *Ballota nigra*.

DCA plot (Fig. 4) showed that these types are well differentiated along the first ordination axis related to both longitude and latitude. It explained 5.7% of the variation in species composition and can be interpreted as a gradient of oceanity-continentality.

3.4.1. Type 1: Open stands with dry-grassland species

This type represents sparse clonal 5–6 (–10) m tall *Robinia* scrubs occurring at the physiological limits of the species and represents a long-lasting successional stage in dry grasslands. Only 20 relevés were recorded from valleys with continental climate in Southern Alps (Fig. 1). Their species-rich understorey is dominated by *Melica ciliata*, increasing in abundance under *Robinia* canopy, and forming only small-sized populations among natural communities on stony and sunny sites. Due to its rapid sprouting ability, *Robinia* creates low open stands rich in steppe perennials and dicots, e.g. from the genera *Festuca*, *Stipa*, *Teucrium* and *Thymus*, and ruderal and steppe annuals such as *Aegilops*, *Bromus*, *Orlaya* and *Tordylium* (Fig. 3 and Tables 3 and A6). Dry-tolerant shrubs such as *Berberis vulgaris* are also common but form a low cover.

This type includes rare and extreme *Robinia* stands (Fig. 4), co-occurring with other *Robinia* types growing under more suitable site conditions. They represent either spontaneous stands or remnants of afforestation efforts on stony pastures, for example in Bulgaria, Serbia, Montenegro, Macedonia and northern Greece. Extensive dwarf *Robinia* stands with a grassy understorey or mixed dwarf stands with *Ailanthus altissima*, widespread in some dry areas, could also be included in this type.

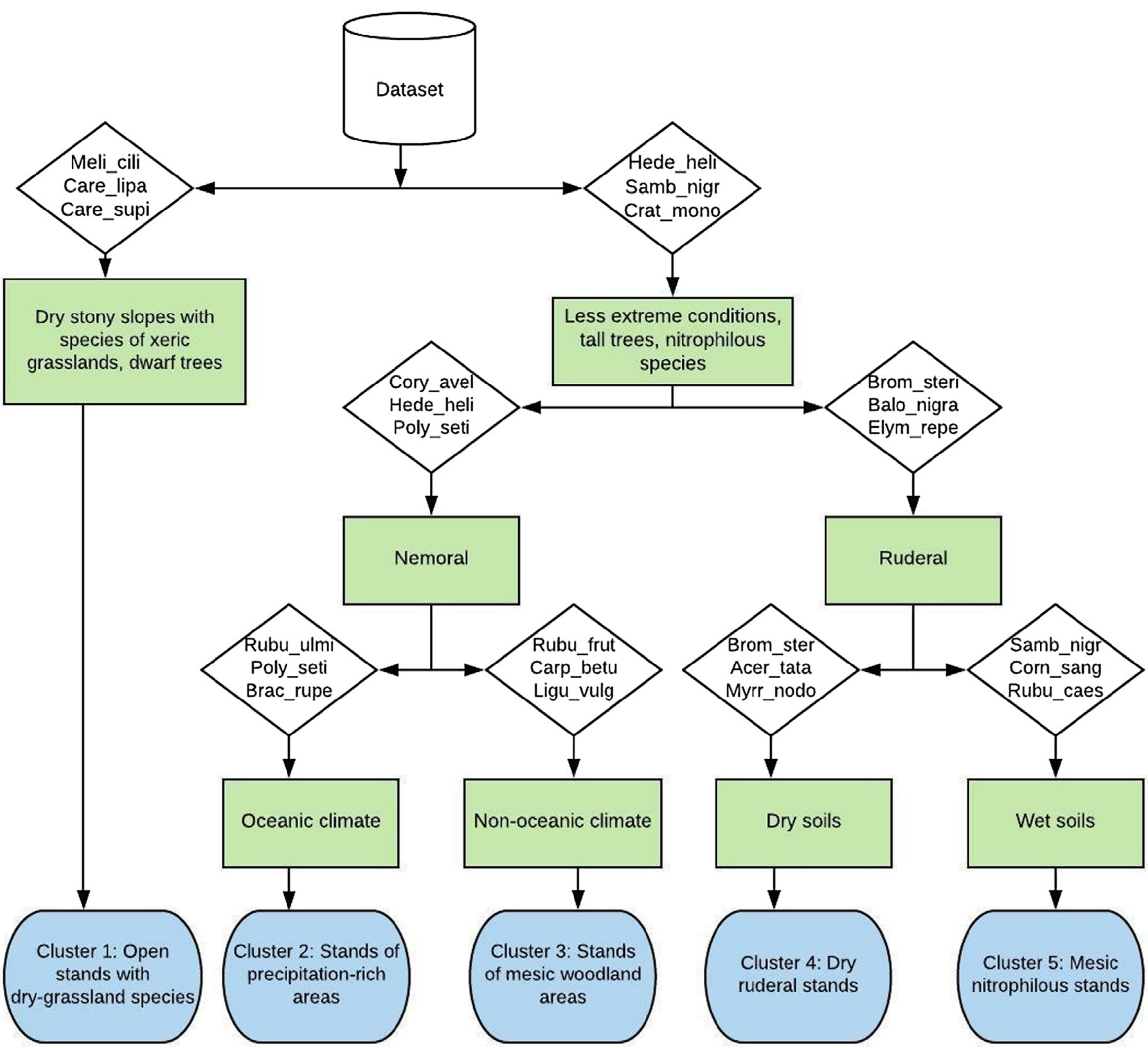

Fig. 3. Numerical classification using modified Twinspan algorithm (Roleček et al. 2009) dividing 467 phytosociological relevés of South European *Robinia* stands into five broad vegetation types according to the main gradients in species composition. Geographical position of relevés is shown in Fig. 1. Species are abbreviated by first letters of their genus and species names.

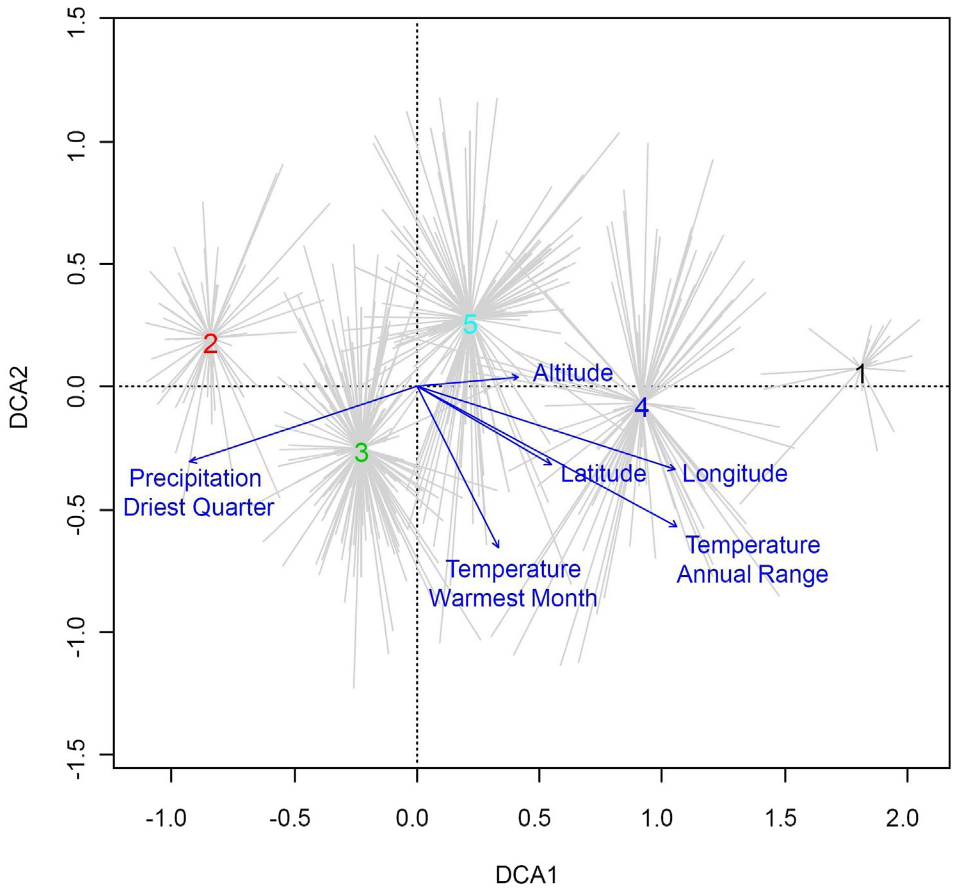

Fig. 4. Spider plot of DCA of five vegetation types of *Robinia* stands in Southern Europe with projected basic geographical and bioclimatic variables. 1. Open stands with dry-grassland species; 2. Stands of precipitation-rich areas; 3. Stands of mesic woodland areas; 4. Dry ruderal stands; 5. Mesic nitrophilous stands.

3.4.2. Type 2: Stands of precipitation-rich areas

This type includes *Robinia* forests with species composition and distribution related to temperate Atlantic-sub-Mediterranean mesophilous oak and ash-maple scree forests, where *Robinia* forms tall pure or mixed stands and dense shrubby thickets. This type is characterized by joint occurrence of (semi-)evergreen Mediterranean woody species (e.g. *Hypericum androsaemum* and *Laurus nobilis*), acidophilous species of temperate-sub-Atlantic distribution (e.g. *Holcus mollis* and *Teucrium scorodonia*) and temperate species of wet nutrient-rich habitats (e.g. *Carex pendula* and *Stachys sylvatica*). The dense understorey is mostly dominated by *Rubus ulmifolius*, *Hedera helix* and many ferns (e.g. *Athyrium filix-femina* and *Pteridium aquilinum*; Figs. 3 and 4; Tables 3 and A6). Low coppiced stands are common and often hardly penetrable due to spiny climbing shrubs such as *Rubus* spp. and *Smilax aspera*. The high frequency of both xerophilous and shade-tolerant species (e.g. *Brachypodium rupestre* vs *Oxalis acetosella*, respectively) may reflect variability within this type, ranging from sunny hills to shady ravines.

Most relevés originate from areas of oceanic climate in northern Spain, but few are also located on the Elba Island (Italy) suggesting a possible wider distribution of this type (Fig. 1). Stands in the oceanic part of south-western France could probably also be assigned into this unit.

3.4.3. Type 3: Stands of mesic woodland areas

This type is associated with mesic temperate-sub-Mediterranean oak, oak-hornbeam and oriental hornbeam forests. Stands of this type are usually rich in mesophilous shrubs (e.g. *Euonymus europaeus* and *Rubus fruticosus* agg.), lianas (e.g. *Clematis vitalba* and *Hedera helix*) and trees (e.g. *Acer campestre* and *Carpinus betulus*). Other frequent woody species are *Corylus avellana*, *Fraxinus ornus*, *Ostrya carpinifolia* and *Quercus petraea* (Figs. 3 and 4; Tables 3 and A6). The ground layer is characterized by mesophilous forest herbs such as *Anemone nemorosa*, *Polygonatum multiflorum* and *Pulmonaria officinalis* agg.

This type is widely distributed across SE from northern Spain to Bulgaria, with the highest number of relevés coming from Italy (Fig. 1). In the Balkan countries, it is probably more common than suggested by available data.

3.4.4. Type 4: Dry ruderal stands

These *Robinia* low forests or shrubby groves originate from both planting and spontaneous spread. They occur in dry habitats of agricultural, ruderal, pastoral and urbanized areas that supply the understorey with many xerophilous ruderal species (Fig. 3; Tables 3 and A6). The stands are often managed as a goat pasture or with frequent topping, pollarding and coppicing. Such disturbances are well tolerated by *Robinia* unlike other woody species that are therefore rare. Among shrubs, dry-tolerant species prevail, such as *Crataegus monogyna* and *Rosa canina*, in the eastern part also *Paliurus spina-christi* and *Acer tataricum*. The herbaceous undergrowth is dominated by ruderal species including short-lived grasses (e.g. *Bromus sterilis* and *Hordeum* spp.), short-lived umbellifers (e.g. *Anthriscus cerefolium* and *Myrrhoides nodosa*), perennial dicots (e.g. *Ballota nigra*) and perennial grasses (e.g. *Elymus repens* and *Poa angustifolia*). The understorey dominated by short-living weeds completely withers and becomes dry during early summer.

This type probably represents the most common SE *Robinia* stands, the available relevés being broadly distributed from France to eastern Romania and abundant especially in Balkan countries (Fig. 1). In most SE cities (e.g. Madrid, Rome, Beograd, Sofia and Tirana) and along highways (e.g. in Spain, Italy and Turkey), semi-spontaneous dry ruderal *Robinia* populations commonly mix with other alien trees such as *Ailanthus altissima*, *Broussonetia papyrifera*, *Gleditsia triacanthos*, *Morus alba* or *Ulmus pumila*.

3.4.5. Type 5: Mesic nitrophilous stands

Species composition of these stands reflects deep, mesic to wet, and summer-dry soils, rich in organic nutrients (Figs. 3 and 4; Tables 3 and A6). In sub-Mediterranean floodplains and shady slopes of valleys, riverine trees such as *Populus alba*, *P. nigra* and *P.* × *canadensis* create an admixture at the tree layer. The dense undergrowth is dominated by mesophilous shrubs (e.g. *Cornus sanguinea* and *Sambucus nigra*), semi-shrub *Rubus caesius*, herbaceous vines such as *Calystegia sepium*, *Humulus lupulus*, tall perennials (e.g. *Anthriscus sylvestris* and *Urtica dioica*) and short spring herbs (e.g. *Ficaria verna* and *Glechoma hederacea*). Many other alien woody species (e.g. *Acer negundo* and *Parthenocissus quinquefolia*) and herbs (e.g. *Artemisia verlotiorum* and *Solidago gigantea*) are also typical.

Distribution of this type ranges from Spain to Romania (Fig. 1). From unpublished data we can infer that this type also occurs in southern Balkan countries such as Montenegro (near Virpazar town), Greece (Nestos River) and Turkey (Meriç River).

3.5. Invaded habitats

Based on inquiries, field research and literary sources, we obtained a list of invaded habitats in individual SE countries (Table A2). The most common include human-made habitats, such as urban, agrarian, industrial, and mining areas (Fig. A3). Most stands belong to vegetation type 4 (see section 3.4.4) where *Robinia* creates mixed groves with other alien woody species in urban greenery and on peripheries of cities. In agricultural landscapes, such as the eastern Po Plain (Italy), *Robinia* is commonly used as hedgerows or vineyard boundaries. Large disconnected groves were planted as a result of afforestation of degraded land, including reclaimed mining areas (e.g. Bulgaria, Greece and Turkey).

In case of planting *Robinia* in the surrounding landscape, mesic and alluvial forests are invaded throughout SE, while invasion into dry forests and scrub is mostly common in Balkan countries (e.g. Bosnia and Herzegovina, Bulgaria and Serbia; Table A2). As a light-demanding species, *Robinia* does not colonize dense forests or shrubland, but can create belts at the margins of mesic forests dominated by oak, oak-hornbeam and beech (e.g. Croatia, Italy and Moldova; vegetation types 2 and 3, see sections 3.4.2 and 3.4.3). *Robinia* often invades disturbed alluvial forests on well drained summer-dry sites (e.g. Albania, Slovenia and Spain; vegetation type 5, see section 3.4.5; Table A2).

Open and disturbed slopes and dry grasslands were the most sensitive to *Robinia* invasion. Afforestation of steep slopes and xeric sites were frequently applied to prevent soil erosion and aridization especially in the Balkan region. Salty and toxic soils were sparsely invaded in SE (Table A2).

3.6. Invasion drivers

Human activities were the main invasion drivers and contain: (i) forestry use including both large projects of afforestation in open landscape and cultivation in local spinneys; (ii) planting for viticulture and orcharding traditionally using *Robinia* wood for vineyard poles and wine barrels; (iii) cultivation for soil protection against erosion and desertification; (iv) linear woodlands, such as protective belts along railways, motorways, roads and rivers; and (v) periurban cultivation of small-scaled stands for multiple uses (e.g. honey, forage, culinary and medicinal). We analysed the effect of each driver on the area occupied by *Robinia*, its residence time and the time since first afforestation (Table A7). The forestry use had a significant effect on all three response variables ($p = 0.014$, 0.034 and 0.056, respectively), viticulture and orcharding was correlated with area ($p = 0.034$) and afforestation ($p = 0.033$), and soil protection only marginally with area ($p = 0.09$; Fig. 5). The effects of linear woodlands and periurban cultivation were not statistically significant. Statistical analysis confirms our expectation based on historical context (see section 3.1) that rapid invasion of *Robinia* is favoured by long-term and large-scale cultivation in the landscape.

3.7. Management

The approaches to *Robinia* reflect differences in cultivation history across SE (Table 2). In Italy, Bulgaria and Romania, *Robinia* has been historically favoured for various purposes (Table 4), while in Albania and Turkey the tree only started to be planted 70 years ago and it is now mainly used for erosion control (Table A2). According to local black lists or national legislation, *Robinia* is considered invasive in most SE countries (Table 5). However, many of the studied countries have no legal restrictions to *Robinia* cultivation, as well as no systematic program targeted to its eradication at valuable sites, despite some regional eradication projects (Table 5).

We distinguish four management types of *Robinia* stands in SE (Table A2 and 4):

(1) **Regularly managed pure *Robinia* forests**. Low forests maintained by coppicing has a long historical tradition across SE, especially in areas with forest grazing or silvopastoral systems like in Basque region and Balkan countries. Recently, this has become the most frequent *Robinia* management due to benefits from high productivity and easy regeneration. In protected areas, woodland structure can be improved by retaining selected standards (optimally native trees) whereas simple coppicing is forbidden. High forests cultivated for timber production are nowadays less popular and occur mainly in agricultural lowlands where other timber is lacking, such as in basins of Drava and Danube rivers. Despite management control, *Robinia* forests present a risk for the biodiversity of surrounding habitats, until they are replaced by native dominants. Light-demanding *Robinia* can spread spontaneously into open landscape, such as abandoned vineyards, orchards and fields, moreover it is able to colonize forest margins or disturbed sites in wooded areas, such as fresh clear-cuts or post-fire sites.

(2) **Regularly managed mixed *Robinia* forests**. Both high and coppiced forests in inter-cropping plantations or originated by decaying of native trees were found. The risk of these stands in terms of invasion is highly context-dependent. Old sparse oak forest with admixture of *Robinia* can represent a transitional stage of succession to native forest, whereas mixed stand of *Robinia* and other aliens, such as *Ailanthus altissima*, *Populus* × *canadensis* or *Gleditsia triacanthos* can cause an environmental threat.

(3) **Intensive short rotation coppice plantations**. These even-aged stands with a short rotation period are mostly planted on farmland for renewable bioenergy production, rarely for forage. If they are adjacent to semi-natural grasslands potentially threatened by forest expansion, a considerable inva-

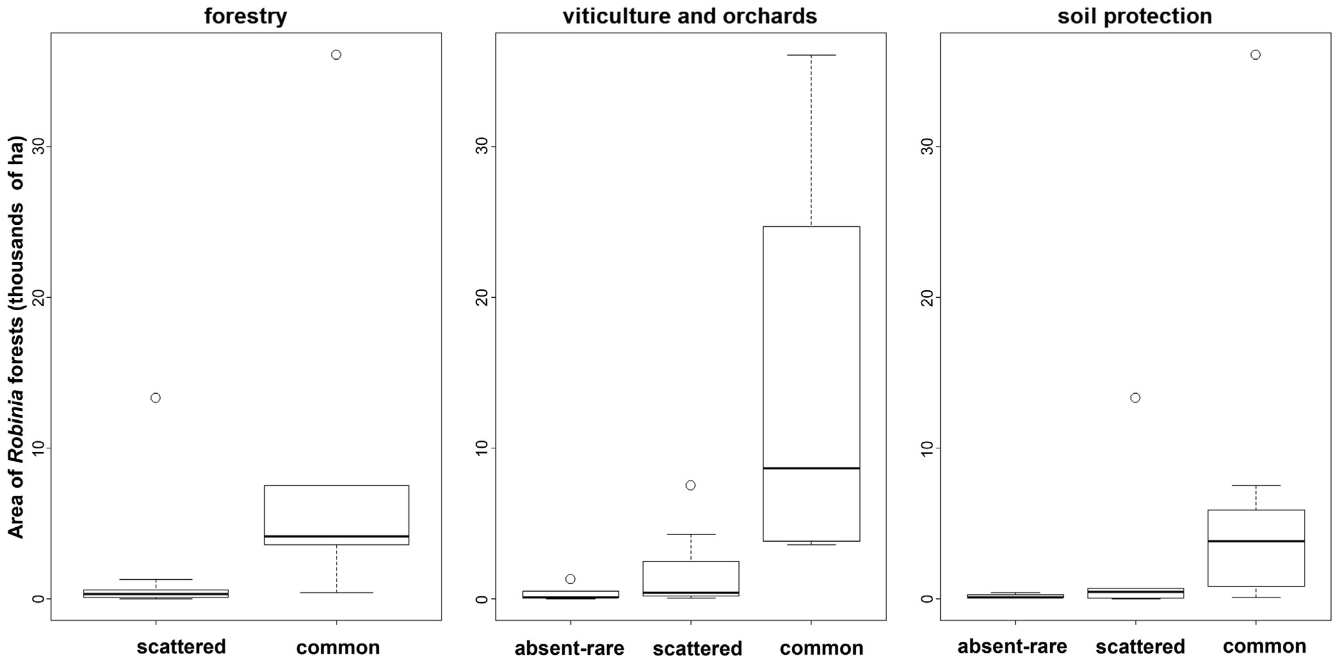

Fig. 5. The area occupied by the *Robinia* forests, depending on the intensity of its utilization in forestry, viticulture and orchards and in soil protection and stabilization. The vertical lines represent the median values across different countries (n=17). The boxes show the 75th and 25th percentiles, respectively. The "whiskers" represent the 1.5 times of the interquartile interval (75th percentile – 25th percentile) and the circles represent the outlier values, exceeding the values of 1.5 × interquartile interval.

Table 4
Utilization of *Robinia* in Southern Europe based on inquiries addressing regional experts (columns B and C) and literature (column D).

Type of utilization		Common use	Examples and references
Products	Timber, firewood, sownwood, veneer, charcoal, pole production	Bulgaria, Croatia, France, Italy, Moldova, Romania, Serbia	Timber, sawnwood and veneer (Bulgaria – Iliev et al. 2005; Romania – Niculescu et al. 2018; Croatia – Perić et al. 2017); production of small wood and domestic use of local owners (Portugal, Spain, Slovenia, Bosnia and Herzegovina – e.g. Hasenauer et al. 2017); charcoal production (Italy - Servant et al. 2006; Moldova – Postolache, 2004); firewood (many countries, e.g. Bulgaria – Iliev et al. 2005; Greece – Alizoti 2017; Moldova – Postolache, 2004; Romania – Niculescu et al. 2018).
	Apiculture, medicinal or culinary products	Bulgaria, Croatia, France, Italy, Macedonia, Romania, Serbia, Spain, Turkey	Honey production (most countries, mainly Turkey – BOEP, 2013; Sivacioğlu and Şen, 2017; Bulgaria – Iliev et al. 2005; Romania – Niculescu et al. 2018); medicinal use (Kosovo – Mustafa et al., 2012; Italy – Pieroni and Quave 2005; Moldova – Postolache, 2004; Serbia – Popović et al., 2012; Romania – Pieroni et al., 2015).
	Bioenergy	Italy, Moldova, Spain (Greece, Albania)	Short-rotation plantations, mainly Italy (Gasol et al., 2010; Manzone et al., 2015; Crosti et al., 2016); Moldova – developing a bioenergy program (Gulca, 2009); utilisation of wood and wood processing residues from existing forests (Serbia – Ilić et al., 2004; Greece – EUBIONET, 2003).
Landscaping	Protective plantations	Albania, Bulgaria, Croatia, Italy, Macedonia, Moldova, Romania, Serbia, Turkey	Soil protection, improvement, stabilization of slope (most countries, e.g. Iliev et al., 2005; BOEP, 2013; Hasenauer et al. 2017). Afforestation of badlands, sand dunes or mine heaps (Romania – Niculescu et al. 2018; Pele et al. 2008; Moldova – Postolache, 2004; Slovenia – degraded Karst regions, Brus et al., 2017; Turkey – Keskin and Makineci, 2009). Mixed stands planted as shelterbelts along roads and railways (most countries, e.g. BOEP, 2013; Marchante et al., 2014; Maslo, 2016; Niculescu et al. 2018).
	Forest grazing, silvopastoral system	France, Spain, south-eastern Europe	Basque areas (Spain, France) and most countries of south-eastern Europe (e.g. Mosquera-Losada et al., 2004). Fodder tree for direct consumption or dried food for domestic animals – Macedonia (Kraljic, 1960), Spain (Mosquera-Losada et al., 2004), Greece (Ainalis and Tsiouvaras, 1998; Papachristou and Papanastasis, 1994).
	Ornamental cultivation	Bosnia and Herzegovina, Bulgaria, Croatia, Italy, Macedonia, Montenegro, Portugal, Romania, Serbia, Spain, Turkey	Most countries, often restricted to settlements. Turkey – landscaping areas for recreational purposes (BOEP, 2013).

Table 5
Invasiveness of *Robinia pseudoacacia* and its local acceptance in the countries studied.

Country	Invasiveness	Black list/Legislation	Legal restriction of planting	Eradication projects
Albania	nat/inv*	–	–	–
Bosnia and Herzegovina	inv	–	–	–
Bulgaria	inv	–	×	×
Croatia	inv	×	–	–
France (Southern)	inv/nat***	×	×	×
Greece	nat/inv**	–	×	–
Italy	inv/nat****	×	×	×
Kosovo	nat	–	–	–
Macedonia	inv	×	?	–
Moldova	inv	×	×	×
Montenegro	inv	×	–	–
Portugal	inv	×	×	×
Romania	inv	×	–	×
Serbia	inv	×	–	x
Slovenia	inv	×	×	×
Spain	inv*****	–	–	×
Turkey (European)	nat	–	–	–

Symbols: **inv** invasive, **nat** naturalized. × yes, **–** no, **?** no data.
*eastern part of Albania; **nordern part of Greece; ***Corse; ****Puglia, Sardinia and Sicily, ******Robinia* is considered invasive, but not mentioned in valid legislation (BOE, 2013)
References: **Albania**: Barina et al. (2014); Metaj, pers. com.; **Bosnia and Herzegovina**: Cero et al. (2016); Maslo (2016); Cvjetković et al. (2017); **Bulgaria**: Petrova et al. (2013); Petkova et al. (2017); www.esenias.org; **Croatia**: Boršić et al. (2008); Đodan and Perić, pers. com.; **France**: GT IBMA (2016); Paule et al. (2017); https://ec.europa.eu/easme/en/life; **Greece**: Arianoutsou et al. (2010); Papaioannoua et al. (2016); Alizoti (2017); **Italy**: Celesti-Grapow et al. (2009); Sitzia et al. (2016b); Monteverdi et al. (2017); Galasso et al. (2018); **Kosovo**: Maxhuni, pers. com.; **Macedonia**: Andonovski and Mandjukovski (2017); www.esenias.org; Simovski, pers. com.; **Moldova**: Postolache (2004); www.biotica-moldova.org; http://www.moldsilva.gov.md/; **Montenegro**: Stešević and Petrović (2010); Bataković et al. (2014); **Portugal**: Ministério do Ambiente (1999) ; Marchante et al. (2014); Tomé et al. (2017); www.invasoras.pt; **Romania**: Sîrbu and Oprea (2011); Mihai et al. (2012); Szatmari (2012); https://ec.europa.eu/easme/en/life; **Serbia**: Lazarević et al. (2012); Andrašev et al. (2017); **Slovenia**: Jogan et al. (2012); Mihai et al. (2012); Brus et al. (2017); **Spain**: Elorza et al. (2004); GEIB (2006); BOE (2013); Castro-Díez et al. (2017); **Turkey**: Sivacioğlu and Şen(2017); Atasoy and Çorbacı (2018); Yazlik, pers. com.

sion risk will result from the cessation of pasture or mowing. *Robinia* suckers form secondary dense stands much faster than native woody species and changes soil environment, as already mentioned above.

(4) **Stands in open land**. These common, small-scale stands, are scattered in open landscape or settlements, hence they are often overlooked by both foresters and nature conservationists. Their environmental impact and related management are site-specific and may differ locally. For example, young spreading stands represent uncontrolled local invasion with critical impact on biodiversity if they occur close to semi-natural habitats, but they are rather harmless in ruderal environments or even a source of novel biodiversity and ecological niches in otherwise completely artificial environments of the cities. Protective stands planted on extremely degraded soils and steep slopes are included in this category.

4. Discussion

4.1. Distribution

Robinia is the most extensively cultivated alien tree in CE and SE (e.g. Křivánek et al., 2006; Nicolescu et al., 2018). In SE, *Robinia* was promoted only after successful testing as a promising forest tree in CE, mainly in Hungary and Germany (Vítková et al., 2017). Sparse plantations established by small-scale afforestation projects (e.g. Piccone, 1796) were followed by extensive campaigns running in some countries between 1850 and 1950 (Fig. 6; e.g. Călinescu, 1941; Iliev et al., 2005; Gulca, 2009), and the process is still accelerating in several Balkan countries (e.g. Bulgaria, Moldova, Romania and Serbia; Jovkovic, 1950; Milosevic, 1950; Nicolescu et al., 2018).

A geographic range of periurban cultivation is much broader than that of plantations in natural conditions. Altitudinal distribution of *Robinia* is controlled by climate. Individual *Robinia* trees reach up to 1640 m a.s.l. in SE (Southern Alps; Sitzia et al., 2016a), while in CE there are only hardly surviving clonal patches over altitude of 500 m a.s.l. (Vítková et al., 2017). The main area of cultivation and invasive spread of *Robinia* is lowlands of both SE (Sitzia et al., 2016a) and CE (Cierjacks et al., 2013; Vítková et al., 2017), which is related rather to the historical utilization of the landscape than climatic and soil differences – as illustrated by the fact that both oceanic lowlands in northern Germany and warm lowlands along Danube harbour abundant *Robinia* populations.

4.2. Species composition and ecology

Our classification in five broad vegetation types is the first large-scale system for *Robinia* in SE. Types 1 and 2 in this study are specific and clearly distinguishable from other vegetation types. Open stands with dry-grassland species (Type 1) represent rare and extreme type described as a separate association *Melico ciliatae-Robinietum* (Wilhalm et al., 2008). These dwarf dry stands are replaced by other *Robinia*-dominated vegetation types on more suitable sites. They are ecologically analogous to CE association *Melico transsilvanicae-Robinietum* (Vítková and Kolbek, 2010). *Robinia* forests of Type 2, characteristic for precipitation-rich areas, are expected to have analogues impoverished in thermophilous species in the oceanic regions of northern France and British Isles. Vegetation types 3 to 5 require further study and a detailed comparison with validly published syntaxa is needed. The admixture of mesophilous nemoral trees, shrubs and herbs characterizing mesic woodlands of Type 3 occurs also in CE association *Chelidonio majoris-Robinietum* (Vítková and Kolbek, 2010). The SE type differs by sub-Mediterranean species, such as *Asparagus acutifolius, Helleborus bocconei* and *Lamium orvala.* Dry ruderal stands of Type 4 are rich in pasture and ruderal species. Their analogues reach up to Pannonian region in the north (Hungary, Czech Republic; e.g. Pócs, 1954 and own unpublished data) and Tunisia in the south where the ruderal *Robinia* stands with undergrowth dominated by *Bromus diandrus, Galactites tomentosus* and *Torilis arvensis* occur (e.g. Aïn Draham region, own unpublished data). Mesic nitrophilous stands of Type 5 have similar species composition to semi-

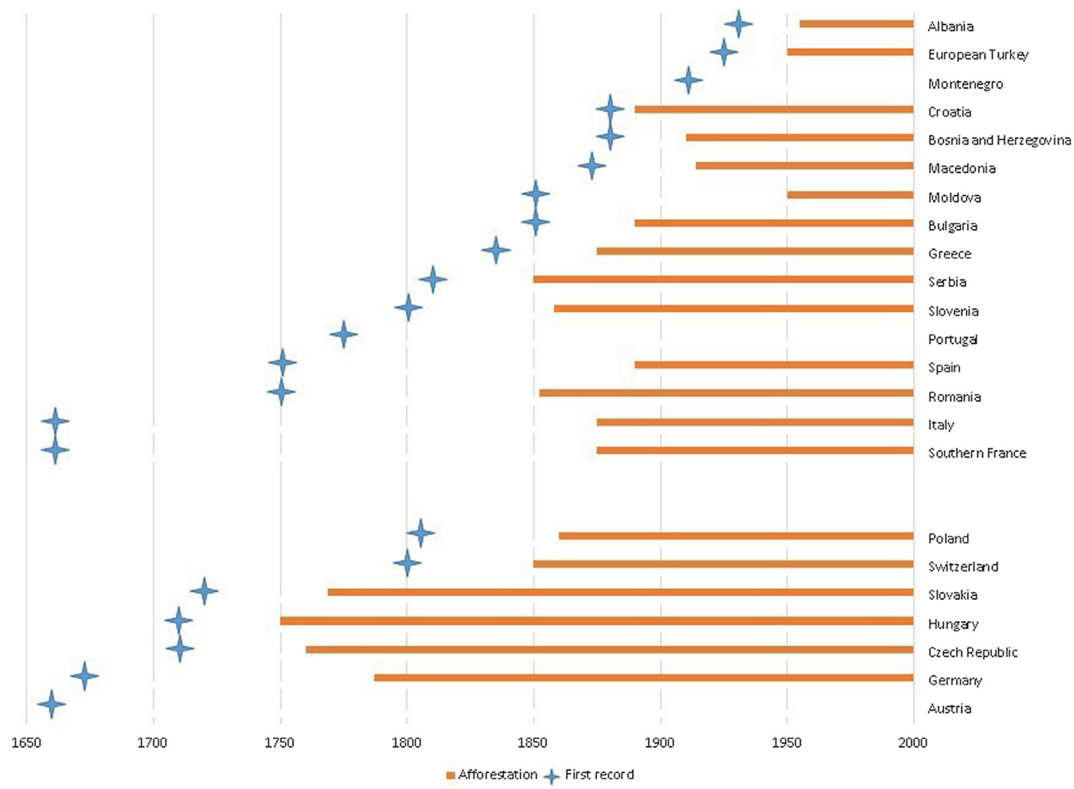

Fig. 6. Comparison of the cultivation history of *Robinia* between Southern and Central European countries. Data for Kosovo are missing. Data from Central Europe were obtained from Vítková et al. (2017).

spontaneous shrubby or tree stands in floodplains and periurban zones of eastern and south-eastern Europe (Arepieva, 2012; Golovanov and Abramova, 2013; Batanjski et al., 2015; Golub and Bondareva, 2017) and CE (Chytrý et al., 2013). Those are often dominated also by other aliens such as *Acer negundo*, *Amorpha fruticosa* and *Fraxinus pennsylvanica*.

The ecological characteristics of the five distinguished vegetation types confirm that *Robinia* is a habitat generalist growing in dry to moderately wet habitats ranging from urban to agricultural landscape, to forest and natural grassland. In SE, natural seed dispersal is only effective in areas with high soil temperatures and/or disturbed bare soils, such as sand dunes (e.g. in Romania; Szatmari, 2012), gravely bare soils along rivers (e.g. Spain, Italy, France and Montenegro; Castro-Díez et al., 2009; Terwei et al., 2013), transport corridors (across SE; e.g. Marchante et al., 2014; Maslo, 2016; Shehu et al., 2014), reclaimed mine spoils (e.g. Bulgaria, Greece, Romania and Turkey; Keskin and Makineci, 2009; Vlachodimos et al., 2013), and post-fire sites (e.g. Italy and Greece; Maringer et al., 2012). Clonal spread allows *Robinia* to easily escape from cultivation, therefore most of the invaded habitats in SE occur near its current and abandoned plantations.

4.3. Utilization and management

Robinia is broadly used in forestry and for landscaping across SE. Forestry use and residence time are main drivers of invasion similarly as in CE (Křivánek et al., 2006) but other large-scale human activities, such as soil protection or production of vineyard poles are also important. Unlike in CE countries where *Robinia* is historically cultivated for timber production in high forests (e.g. Vadas, 1914; Göhre, 1952), traditional forest management in SE includes a combination of silvopastoralism, coppicing, short-rotation forestry and variety of uses (e.g. Horvat et al., 1974). The range of *Robinia* utilization is much broader in SE than in CE, including both modern industrial processing and traditional rural uses. Especially in rural areas, the stands are multi-purpose, used for soil stabilization, wood production (i.e. timber, poles, roundwood, fuelwood and charcoal), non-wood products (i.e. fodder, honey, cosmetics and medicines), forest grazing, recreation, aesthetic and cultural purposes (e.g. Papachristou and Papanastasis, 1994; Postolache, 2004; Iliev et al., 2005; BOEP, 2013). *Robinia* is planted to supplement natural sparse stands degraded by coppicing, overgrazing or decaying of native trees after windthrows or epidemics, such as chestnut blight or aggressive root pathogen *Phytophthora cinnamomi* in oak forests (e.g. Thomas, 2008; Motta et al., 2009; Mosquera-Losada et al., 2012). Other inter-cropping plantations combined *Robinia* with various woody species including aliens to improve soil quality, yield and resistance to abiotic and biotic disturbances or diversity of food supply and nesting possibilities for birds (Guidi and Piussi, 1993; Benesperi et al., 2012; Kroftová and Reif, 2017). On the other hand, mixed stands can cause environmental problems due to invasiveness of alien trees (e.g. Medina-Villar et al., 2015; Lóczy, 2019).

Robinia plantations focusing only on production of wood or renewable bioenergy are less common in SE than in CE. Extreme caution should be taken following abandonment of plantations, because there is a great risk of *Robinia* invasion, depending on land cover types in the vicinity. The most threatened are abandoned arable land (Crosti et al., 2016), and dry and semi-dry grasslands (Vítková et al., 2017). Regularly managed buffer zone surrounding *Robinia* plantations should act as a biological barrier against resprouting root suckers (Crosti et al., 2016). Another problem is low succession rate due to depletion of nutrients in topsoil caused by low production of litter and periodic removal of organic matter, changed light regime and shift of species composition towards ruderal plant species (Vasilopoulos et al., 2007). In several countries, such as Moldova, Turkey and Albania, cultivation of *Robinia* for afforestation of highly degraded soils is the most important use (e.g. Postolache, 2004; BOEP, 2013; Enescu and Dănescu, 2013; Cvjetković et al., 2017). Although *Robinia* grows in subhumid to humid conditions in its native range, it was successfully introduced to many parts of the world where climatic conditions are much drier (Huntley, 1990). Very dense and plastic root systems with long horizontal ramets (Benčať, 1988) together with ecophysiological adaptations (e.g. Xu et al., 2009; Minucci et al., 2017) and fast recovery after drought stress (Moser et al., 2016) makes *Robinia* relatively drought tolerant in comparison with other native deciduous tree species.

4.4. Biodiversity conservation

Research on this species accumulated a body of evidence that the concerns resulting from its dominance as an invasive alien tree is justified. Pervasive metapopulations fundamentally threaten native ecosystems (e.g. Wilhalm et al., 2008; Mihai et al., 2012) and local biodiversity (e.g. Matus et al., 2003), and their later eradication would be costly and time-consuming with uncertain results (Vítková et al., 2016; Sádlo et al., 2017). Decrease in species diversity of *Robinia* stands in CE is caused by structural homogenization (Šibíková et al., 2019), soil eutrophication (Vítková et al., 2015) and dominance of nitrophilous ruderal species (Vítková and Kolbek, 2010) in tall and shady monocultures (Rédei et al., 2014) which remain unmanaged for many decades in several countries (e.g. Czech Republic, Switzerland) and even small-scale disturbances are rare (Vítková et al., 2018). On the other hand, *Robinia* stands are often mixed, light and heterogeneous in SE, thus the impact of *Robinia* is mitigated by share of other native trees, such as oaks. The homogenizing effect of the species is controversial, particularly in rural landscapes (Sitzia et al., 2012), but the species composition (Nascimbene et al., 2012; Campagnaro et al., 2018b; Allegrezza et al., 2019) and ecosystem processes (Sitzia et al., 2018) are always changed in comparison with native tree stands. Diverse forms of silvopastoral management (Rigueiro-Rodríguez et al., 2009) combined with coppicing (Vacik et al., 2009) are often used due to historical reasons, especially in Balkan countries. Optimal management intensity supports a variety of small-scale disturbances, creating a wide range of light and shade conditions, coexistence of nutrient-poor and rich sites and heterogeneous vertical and horizontal vegetation structure (Bergmeier et al., 2010). In dry open habitats, water stress leads to stunted growth and dwarfism of *Robinia* (Jin et al., 2011), which together with its slow propagation, weak nitrification and shading effect (Vítková et al., 2015; Sádlo et al., 2017) allow for the survival of native flora and fauna.

In habitats and species of conservation value, the impact of *Robinia* is still a major one in SE. However, a small proportion of pure or mixed *Robinia* stands in the landscape may even increase its structural, functional and cultural diversity (Fig. A3; Campagnaro et al., 2018b), especially in urban areas (Sitzia et al., 2016c). Therefore, complementary approaches to mitigate risks related to the use of invasive *Robinia* in plantations should be further investigated, implemented, and regularly revised (Brundu and Richardson, 2016). A site-specific management for planted or spontaneous *Robinia* woodlands will consider several stand scale options, such as reducing or suspending coppicing, particularly of stands that are close to valuable open habitats, such as Natura 2000 habitat types. Furthermore, the maintenance, through mowing or grazing, of the adjacent open habitats would increase their resistance to invasion (Sitzia et al., 2016b). The technical regional literature provides many examples of how the invasiveness of *Robinia* can be controlled and its beneficial services should be valued without threatening other ecosystem services provided by adjacent forests and non-forested habitats. Mullaj et al. (2017) offer environment-friendly solutions to select native resistant species instead of aliens for reforestation of degraded lands and urban environments.

5. Conclusions

We provide an original comparative and synthetizing study evaluating the environmental impact of *Robinia* at local and regional scales in Southern Europe, based on a new vegetation analysis linking with ecological and cultural aspects. Although *Robinia* is a controversial invasive alien tree species, it is established as a constant component of landscapes, which is evidenced by the fact that in some countries it is sometimes perceived as native (e.g. Turkey), and has become an important part of the economy in other countries (e.g. Bulgaria, Romania). We explored both sides of *Robinia* planting and related context: (i) distribution of *Robinia* in SE, (ii) regional differences in its cultivation history, (iii) diversity of habitats, vegetation and management approaches, (iv) invasiveness and associated problems to nature protection, (iv) ecological risks vs multifaceted utilization of this alien tree; (iv) and drivers and constraints determining the current distribution of *Robinia* with potential future impacts of this invasion.

The enthusiasm for *Robinia* cultivations given by its wide habitat tolerance and miscellaneous utilization is easily understandable. Historical experience clearly shows that almost all countries, in which the tree was successfully established, underwent a phase of large-scale cultivation and afforestation. Our results confirm that it is difficult to answer an important question, whether *Robinia* should be cultivated and promoted, widely tolerated, or eradicated as a dangerous invasive alien in the landscape of SE. Clear recommendations can be concluded on a local scale only, for example in case of cultivated *Robinia* forests vs neighbouring spontaneous stands spreading into valuable habitats with endangered species. Highly variable landscape of SE, both in terms of natural and cultural environment, requires a stratified approach. Each decision must be highly context-dependent, simultaneously accounting for regional attitude to cultivation of *Robinia* and ecological, conservation, and economic aspects.

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Authors' contributions

This study was conceived and led by Michaela Vítková and Jiří Sádlo who obtained all data and also wrote the manuscript. Jan Roleček mainly conducted statistical analyses, Petr Petřík managed the JUICE databases, Tommaso Sitzia provided several relevés from Italy, and supervised the management and legislation topics. Jana Müllerová created the map of distribution and invasion risk in a GIS environment. Petr Pyšek was a supervisor of the study who helped with valuable comments to improve the final work. All authors discussed the results, commented on the manuscript as it progressed, approved the final version to be published and agreed to be accountable for the aspects of the work.

Conflict of interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134857.

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