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Predicting abundances of invasive ragweed across Europe using a "top-down" approach

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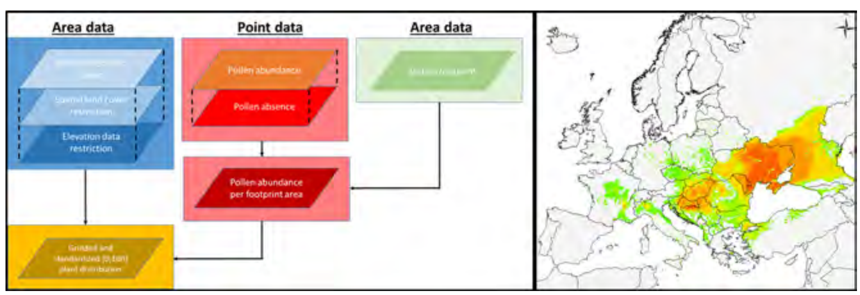
HIGHLIGHTS

- An approach for distribution modelling of anemophilous species using pollen data
- Validated against plant observations of ragweed and cross validation
- European-wide coverage revealing many new invaded regions.
- 1 km & 10 km inventories covering all of Europe.

GRAPHICAL ABSTRACT



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ABSTRACT

Common ragweed (*Ambrosia artemisiifolia* L.) is a widely distributed and harmful invasive plant that is an important source of highly allergenic pollen grains and a prominent crop weed. As a result, ragweed causes huge costs to both human health and agriculture in affected areas. Efficient mitigation requires accurate mapping of ragweed densities that, until now, has not been achieved accurately for the whole of Europe. Here we provide two inventories of common ragweed abundances with grid resolutions of 1 km and 10 km. These "top-down" inventories integrate pollen data from 349 stations in Europe with habitat and landscape management information, derived from land cover data and expert knowledge. This allows us to cover areas where surface observations are missing. Model results were validated using "bottom-up" data of common ragweed in Austria and Serbia. Results show high agreement between the two analytical methods. The inventory shows that areas with the lowest ragweed abundances are found in Northern and Southern European countries and the highest abundances are in parts of Russia, parts of Ukraine and the Pannonian Plain. Smaller hotspots are found in Northern Italy, the Rhône Valley in France and in Turkey. The top-down approach is based on a new approach that allows for cross-continental studies and is applicable to other anemophilous species. Due to its simplicity, it can be used to investigate such species that are difficult and costly to identify at larger scales using traditional vegetation surveys or remote sensing. The final inventory is open source and available as a georeferenced tif file, allowing for multiple usages, reducing costs for health services and agriculture through well-targeted management interventions.

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1. Introduction

Common ragweed (*Ambrosia artemisiifolia* L.) is an invasive species that occupies many different ecosystems (Essl et al., 2015; Smith et al., 2013). The plant is a major weed in crop fields, but has achieved notoriety for its worldwide impact on human health. *Ambrosia* is anemophilous and its pollen is an important aeroallergen and significant cause of seasonal asthma and rhinitis where the plant is recorded (Smith et al., 2013; White and Bernstein, 2003). Common ragweed is particularly abundant in the Northern Hemisphere and its presence results in high atmospheric concentrations of pollen in North America (Zhang et al., 2015), where it is native, and regions outside of its native range such as China (Li et al., 2012; Sun et al., 2017c) and Europe (Essl et al., 2015; Sikoparija et al., 2017), where the plant has invaded vast geographical areas covering thousands of kilometres. In Europe, sensitisation rates to *Ambrosia* pollen allergens range from <2.5% in Finland to >50% in known centres of ragweed infestation such as Budapest, Hungary (Burbach et al., 2009; Heinzerling et al., 2009; Sikoparija et al., 2017; Smith et al., 2013).

A mature common ragweed plant can produce more than a billion pollen grains (Fumanal et al., 2007) that, due to their small size, frequently undergo continental scale atmospheric transport (Šikoparija et al., 2013; Smith et al., 2013). Common ragweed has been observed to increase its pollen production under higher CO_2 concentrations (Rogers et al., 2006) and within urban environments (Ziska et al., 2003). Under climate change, the plant is projected to expand its range in Europe to the north and east (Sun et al., 2017a, b). Airborne concentrations of *Ambrosia* pollen are expected to increase due to the plant's accelerated invasion into new ecosystems, its increased pollen production, and enhanced atmospheric transport (Hamaoui-Laguel et al., 2015). Similarly, recent findings suggest possible expansion of its range in North America at the northern margins of its current distribution and contraction to the south (Case and Stinson, 2018), as well as towards north and east in East Asia (Sun et al., 2017c). Suitable habitats and distribution of common ragweed have been modelled for present and future conditions in Europe (Essl et al., 2015; Sun et al., 2017b), but inventories documenting abundances across whole continents including Europe are largely absent.

Knowledge of abundances of common ragweed at the continental scale is important for pollen forecasting (Prank et al., 2013; Zink et al., 2012, 2017) and for mitigation strategies that aim at a sustainable reduction in plant density and pollen exposure. Unfortunately, the availability of the required plant occurrence records of invasive species like common ragweed is often limited (Müller-Schärer et al., 2018). Consequently, the spatial and temporal resolution of abundance data for common ragweed in Europe is very heterogeneous, which hampers mapping of the distribution and abundance of the plant. There have been several attempts to model the distribution of common ragweed using either occurrence data (Bullock et al., 2010) or ecosystem models (Chapman et al., 2014; Rasmussen et al., 2017; Storkey et al., 2014), but all these studies have limitations describing actual abundances (Matyasovszky et al., 2018; Thibaudon et al., 2014). A main constraint is that the invasion of common ragweed is still ongoing in many countries (Karrer et al., 2015; Onen et al., 2014) and management of the landscape often increases invasion (Richter et al., 2013). However, most continental scale ecosystem models do not contain information on nation-specific management of the landscape, as this is difficult to obtain for all Europe when it comes to agriculture (Werner et al., 2015). Remote sensing based methods used to detect common ragweed over large areas are also challenging, especially since pollen-producing plants can be surprisingly small and usually occur in mixed herbaceous vegetation (Essl et al., 2015). Other approaches for creating inventories are therefore needed.

The ragweed beetle *Ophraella communa* LeSage has recently invaded Northern Italy and has been shown to clear large fields of common ragweed (Müller-Schärer et al., 2014, 2018) thereby affecting the overall pollen emission in the area (Bonini et al., 2017) and significantly reducing airborne *Ambrosia* pollen concentrations (Bonini et al., 2015, 2016). If this beetle becomes abundant locally or actively spreads into new areas with large infestations of common ragweed, then this may have a large positive impact on human health (Mouttet et al., 2018). It is therefore important to have complete and up-to-date source maps for common ragweed showing levels of *O. communa* infestation so they can be used for mitigation and pollen forecasting purposes. In addition, the well-documented populations of ragweed in France, Italy and on the Pannonian Plain need to extend to the less well known, but very important, source regions in Ukraine and Russia. This is because atmospheric transport from these areas regularly contributes to airborne *Ambrosia* pollen concentrations recorded in Europe and western Asia; e.g. Poland (Bilińska et al., 2017; Kasprzyk et al., 2011), Denmark (Sommer et al., 2015) and Turkey (Celenk and Malyer, 2017; Zemmer et al., 2012). Furthermore, such data should clearly identify the invasion fronts of common ragweed as the level of infestation in a given area affects the mitigation strategies that are likely to be successful (Milakovic et al., 2014; Lommen et al., 2018). Finally, the quality of the inventories should be validated, ideally using independent data.

The main aim of this study is to produce a validated inventory of ragweed abundance for Europe. This was achieved by developing a new approach that allowed the plant's abundances to be mapped over the entire European Continent and then validating this inventory using both cross validations and independent plant-based occurrence data of common ragweed in Serbia and Austria. The proposed approach is designed to be globally applicable for anemophilous species that are otherwise difficult to map, not just ragweed. Finally, the inventory we present here for ragweed abundances is available as open access in an easy to use format.

2. Materials and methods

2.1. Generalised method for generation of the European ragweed inventory using pollen data

Making inventories of flowering plants can be carried out using two approaches: 1) Bottom-up approaches that typically are produced using statistical analysis of plant abundance or 2) top-down approaches where a measured quantity of pollen as a starting point (Skjøth et al., 2013). For an anemophilous species like common ragweed, spatial data of airborne pollen concentrations can help to construct abundance maps (Müller-Schärer et al., 2018). It has been shown that using pollen data to generate "top-down" inventories for France produced better pollen forecasts than "bottom–up" inventories based on available occurrence data of common ragweed plants (Zink et al., 2017). Top-down inventories based on pollen data have been made available for the Pannonian Plain (Skjøth et al., 2010), Austria (Karrer et al., 2015) and Italy (Bonini et al., 2017). These inventories provided data with different geographical resolutions and as a result had compatibility problems near the boundaries where maps overlapped (Karrer et al., 2015). Furthermore, gaps in available data have prevented the mapping of important ragweed areas such as western Ukraine (Skjøth et al., 2010). Therefore, no European-wide inventory has previously been produced.

Fig. 1 illustrates the most important steps and the datasets needed for producing continental wide inventories. Step 1 is to create a harmonised and geographically consistent dataset (Fig. 1, left column) that includes both the habitats that are populated by the plant (in the case of ragweed this varies geographically, as seen in Table 1). This is then combined with information known to restrict the presence of the plant. The approach for ragweed is described in detail in Section 2.1.1. The second step is to include the presence and absence of pollen data of the plant in question (Fig. 1, middle column). Favourable habitats may or may not be populated by a plant and so the presence/absence of airborne pollen recorded at specific geographical locations is important for determining the plant's coverage. Conceptually, the pollen

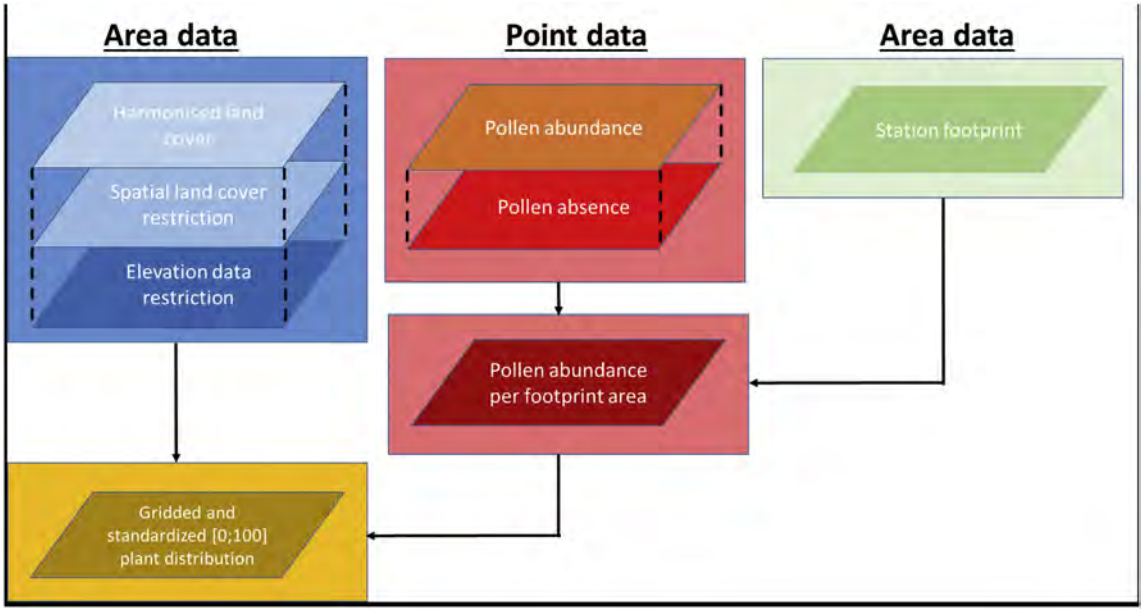

Fig. 1. Conceptual figure illustrating data flow and needed data sets for producing continental-wide inventories using the top-down approach.

data is a point based dataset which can be used to calculate local abundance. The approach for ragweed is described in detail in Section 2.1.2. The last dataset is the station footprint area (Fig. 1, right column). This is used to calculate abundance within a region (e.g. Skjøth et al., 2010; Thibaudon et al., 2014), which is termed the infestation level of the plant (e.g. invasive ragweed). The footprint area can be based on simple circles (Skjøth et al., 2010), the concentric ring method (Oteros et al., 2015) or footprint modelling - backwards modelling using tools such as the atmospheric particle dispersion model HYSPLIT (Stein et al., 2015) or SILAM (e.g. Hernandez-Ceballos et al., 2014). The abundance or infestation level found at the combined set of stations is then interpolated to the entire model domain. This implicitly assumes that the infestation level of the plant in nearby habitats is similar and that a suitable approach to estimate the abundance in regions without observations is to combine the presence of habitats with the abundance of pollen from the nearest observational points.

2.1.1. Inventories of infested habitats

We generated inventories showing the distribution of ragweed abundances in Europe using a combination of airborne pollen data and land cover types identified as having the potential for ragweed invasion – a so called infested habitat approach (Karrer et al., 2015; Skjøth et al., 2010). Experts were consulted about which land cover types (habitats) have the potential to be infested by common ragweed in different areas. This allowed the abundance of habitats that could be infested in a

Table 1
CORINE land cover types with major ragweed infestation in the six regions in Europe described in this study. Suitable habitats are marked with **YES** and less suitable are marked with *No.*

CLC code	CORINE land cover classifications (label 3) currently considered to be major ragweed habitats within Europe (n = 19)	Major ragweed habitats Austria (East & West combined) (n = 17)	Major ragweed habitats France (n = 13)	Major ragweed habitats Italy (n = 11)	Major ragweed habitats Pannonian Plain (n = 7)	Major ragweed habitats Czech Republic (n = 6)	Major ragweed habitats rest of Europe (n = 4)
1.1.2	Discontinuous urban fabric	**Yes**	**Yes**	**Yes**	*No*	**Yes**	**Yes**
1.2.1	Industrial commercial units	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
1.2.2	Road and rail networks and associated land	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
1.2.3	Port areas	**Yes**	*No*	*No*	*No*	**Yes**	**Yes**
1.2.4	Airports	**Yes**	**Yes**	*No*	**Yes**	*No*	*No*
1.3.1	Mineral extraction sites	**Yes**	*No*	*No*	*No*	*No*	*No*
1.3.2	Dump sites	**Yes**	*No*	*No*	*No*	*No*	*No*
1.3.3	Construction sites	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	*No*
1.4.1	Green urban areas	**Yes**	**Yes**	**Yes**	*No*	*No*	*No*
2.1.1	Non-irrigated arable land	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	*No*
2.1.2	Permanently irrigated land	**Yes**	**Yes**	**Yes**	*No*	*No*	*No*
2.2.1	Vineyards	**Yes**	**Yes**	*No*	*No*	*No*	*No*
2.2.2	Fruit trees and berry plantations	**Yes**	**Yes**	*No*	*No*	*No*	*No*
2.3.1	Pastures	**Yes**	*No*	*No*	*No*	*No*	*No*
2.4.1	Annual crops associated with permanent crops	*No*	**Yes**	**Yes**	*No*	*No*	*No*
2.4.2	Complex cultivation patterns	**Yes**	**Yes**	**Yes**	**Yes**	*No*	*No*
2.4.3	Land principally occupied by agriculture, with significant areas of natural vegetation	**Yes**	**Yes**	**Yes**	**Yes**	*No*	*No*
2.4.4	Agro-forestry areas	*No*	*No*	**Yes**	*No*	*No*	*No*
3.2.1	Natural grassland	**Yes**	*No*	*No*	*No*	*No*	*No*

specific region to be calculated. The degree of infestation was then determined by the use of pollen data.

The combined region under investigation included Europe and parts of western Asia (Fig. 2A), which is termed 'Europe' for the purposes of this study. Two land cover datasets were used with high spatial resolution: (1) The Corine Land Cover (CLC) 2012 version, which encompasses the European Union and selected associated countries (Commission, 2005), and includes countries such as Norway, Switzerland, Serbia and Turkey with a grid resolution of 100 m; (2) Globcover (Bicheron et al., 2008), a global land cover dataset that has a coarser resolution (300 m), fewer land cover classes and less detail with respect to management than the CLC dataset, but that allowed us to analyse important ragweed areas like Ukraine and Russia.

The infestation of suitable habitats by **common** ragweed is favoured by soil disturbance and can either be enhanced or suppressed by national agricultural schemes and local management of the agricultural landscape and transport networks (Skjøth et al., 2010). The invasion of common ragweed is ongoing and the plant has yet to colonise all favourable habitats in the studied region, e.g. Austria (Karrer et al., 2015) and Turkey (Onen et al., 2014). The CLC dataset was therefore separated into regions (at NUTS1 and NUTS2 levels) and each region was given its own set of land cover classes following Karrer et al. (2015). These regions that, according to current scientific knowledge, might be infested by common ragweed (Table 1) include: the Pannonian Plain (Skjøth et al., 2010), which we have extended to cover the Balkan region and parts of Turkey (Onen et al., 2014); Austria/Switzerland (Karrer et al., 2015); parts of Italy (Bonini et al., 2017; Celesti-Grapow et al., 2009; Gentili et al., 2017); France (Thibaudon et al., 2014); Czech Republic (Skálová et al., 2017); Northern and Southern Europe. Note that we assume that the main infestation of common ragweed in Northern and Southern Europe is in the urban zone (McInnes et al., 2017; Sommer et al., 2015), an assumption supported by the fact that most observations of common ragweed in these areas have been associated with built environments (Sommer et al., 2015).

The Globcover dataset was used outside the CLC region and separated into two regions in the studied area: South and North (Fig. 2A). According to the Interactive Agricultural Ecological Atlas of Russia and neighbouring countries, common ragweed is found abundantly in southern Russia, Georgia and parts of Ukraine (Afonin et al., 2008). To the East, this information is limited as Kazakhstan was not covered by the Russian Atlas. The northern region covers Belarus, the northern parts of Ukraine and central and northern Russia. In this northern Globcover region, the urban zone (ID = 190) was considered the only habitat for common ragweed. In the southern region, the main agricultural land cover classes (ID = 11,14,20,30) and the urban zone were considered to be the only habitats for common ragweed following Afonin et al. (2008). The completed Globcover dataset was reprojected and re-gridded to 100 m × 100 m and combined with the CLC dataset.

As with previous studies (Bonini et al., 2017; Karrer et al., 2015; Thibaudon et al., 2014), an elevation filter was used because common ragweed is known to mainly occupy lowlands and permanent populations are only found below the climatological limit favouring the plant's growth (Essl et al., 2009; Karrer et al., 2015). Studies have shown that this climatological limit, where ~99% of stable populations are found below, ranges from 439 m a.s.l. in France (Thibaudon et al., 2014) to 745 m a.s.l. in the Alpine region of Austria (Karrer et al., 2015). Casual populations of common ragweed have been identified up to 1100 m a.s.l. in Europe (Essl et al., 2009), but practically no *Ambrosia* pollen is observed above 1000 m (Matyasovszky et al., 2018). Although it should be noted that Gentili et al. (2017) observed the plant growing up to 1834 m a.s.l. in Italy. In this study, the altitudinal limit of 745 m was

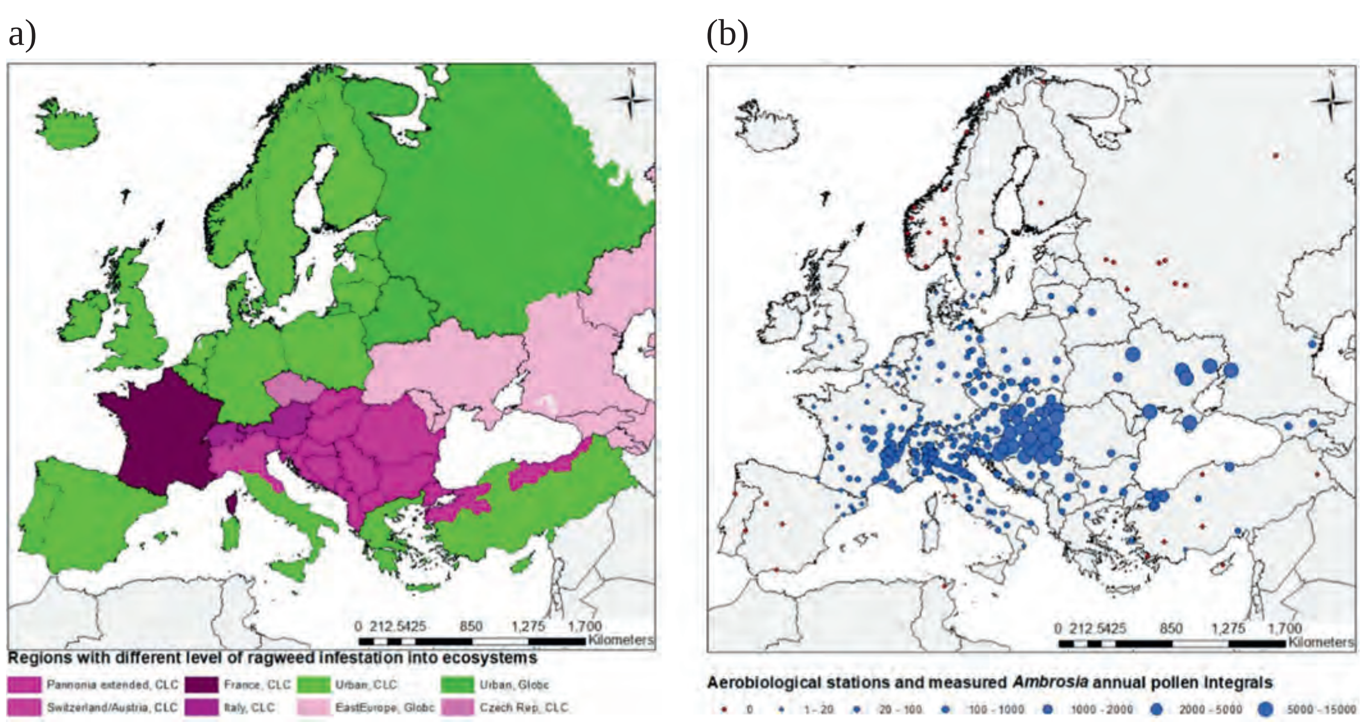

Fig. 2. A: Geographical regions with different invasion levels of common ragweed in described land cover classes within the Corine Land Cover (CLC) classification separated into the following six zones as described in Table A1: (1) The Pannonian Plain extended to cover part of the Balkans and parts of Turkey, (2) France, (3) Austria extended to cover Switzerland, (4) Czech Republic, (5) Parts of Italy and (6) areas with limited invasion and mainly in the urban zone (Sommer et al., 2015; McInnes et al., 2017). The coarser Globcover classification is separated into two regions with ragweed invasion found in the rural landscape covering mainly Ukraine and southern Russia and northern parts where ragweed is only expected to be found in the urban landscape. **B**: Pollen-monitoring sites included in this study with a defined pollen integral and additional sites with no records of ragweed pollen.

chosen as a general filter for Europe, except for France where the more restrictive 439 m filter was used due to the lower infestation in elevated terrain (Thibaudon et al., 2014).

The elevation filter is based on two datasets in order to cover all of Europe with sufficient accuracy. The first is the global void filled dataset from the NASA Shuttle Radar Topographic Mission (Reuter et al., 2007) that was made available at 90 m resolution up to 60 degrees North (Jarvis et al., 2008). The second, which we used beyond 60 degrees North, is the 225 m dataset from USGS named the Global Multi-resolution Terrain Elevation Data 2010 (Danielson and Gesch, 2011). Both datasets were reprojected and re-gridded to 100 m grid resolution defined by the CLC dataset. The elevation filter was applied on the combined land cover data set with ragweed habitats and this final dataset was re-gridded to 1 km for further manipulation including the application of pollen data.

2.1.2. Pollen data and calculation of infestation level

Pollen data (2004–2012) obtained from published work were included in the study (Fig. 2B). An additional ±2 years was allowed to ensure that sufficient data points in the vicinity of the main invasion fronts of common ragweed were included, covering regions like Spain, the UK, parts of France, North Western Europe and Northern Russia. The published work contained pollen data collected using optical methods for identification and enumeration and displayed with well-defined pollen integrals according to Galán et al. (2017). *Ambrosia* pollen data obtained using this approach may include pollen from several species of ragweed that are present on the European continent, while common ragweed is the most widespread of all species (Smith et al., 2013).

The pollen data encompass all the main centres in Europe infested by common ragweed, i.e. Italy (Bonini et al., 2017), Austria (Karrer et al., 2015), the Pannonian Plain (Skjøth et al., 2010), France (Thibaudon et al., 2014) and parts of Ukraine. Additional published data from 18 countries were included from a European-wide trend study concerning *Ambrosia* pollen (Sikoparija et al., 2017). Further data were included from studies conducted in Germany (Buters et al., 2015; Höflich et al., 2016; Melgar et al., 2012), Croatia (Bokan et al., 2007; Liu et al., 2016; Menut et al., 2014; Peternel et al., 2006; Puljak et al., 2016), Turkey (Acar et al., 2017; Altintaş et al., 2004; Bicakci and Tosunoglu, 2015; Tosunoglu and Bicakci, 2015), Romania (Leru et al., 2018), Russia (Severova et al., 2015; Shamgunova and Zaklyakova, 2011), Serbia (Josipović and Ljubičić, 2012), Ukraine (Maleeva and Prikhodko, 2017; Rodinkova, 2013; Turos et al., 2009), Bosnia (Turos et al., 2009) and Slovakia (Hrabovský et al., 2016). All these sites are located within urban zones and data are collected from the top of a building, typically 10 m–20 m above ground level.

Additional calibration points outside the main centres for common ragweed were obtained by conducting a literature review of published studies (e.g. pollen calendars) during the selected time period taking into account both rural and urban locations. This was used to document the minimal presence or absence of airborne *Ambrosia* pollen as an indication of the current invasion front. Studies were included when they either reported full pollen calendars without ragweed, thereby documenting low or no occurrence of *Ambrosia* pollen or specific numbers with respect to low amounts of ragweed pollen. This literature review, as well as the main data collection of pollen integrals, took into account both English and non-English literature found within the study region such as Norwegian, Serbian and Russian. This provided data of limited or no presence of airborne *Ambrosia* pollen from the following regions: Porto, Portugal (Ribeiro and Abreu, 2014), Funchal, Portugal (Camacho, 2015), Toledo, Spain (Garcia-Mozo et al., 2006; Perez-Badia et al., 2010) Badajoz, Spain (Gonzalo-Garijo et al., 2006), Salamanca, Spain (Rodríguez-de la Cruz et al., 2010), Nerja, Spain (Docampo et al., 2007), Moscow, Russia (Volkova et al., 2016), Mornag, Tunisia (Hadj Hamda et al., 2017), Nicosia, Cyprus (Gucel et al., 2013), Bodrum, Turkey (Tosunoglu and Bicakci, 2015), Konya, Turkey (Kizilpinar et al., 2012), Kastamonu, Turkey (Çeter et al., 2012), Denizli, Turkey (Güvensen et al., 2013), Van, Turkey (Bicakci et al., 2017), Hatay, Turkey (Tosunoglu et al., 2018), Perm, Russia (Novoselova and Minaeva, 2015), 12 sites from Norway (e.g. Bicakci et al., 2017; Tosunoglu et al., 2018) Finland (Manninen et al., 2014) and 5 sites from central/northern Russia that documented no *Ambrosia* pollen deposition from the air (Nosova et al., 2015).

Note that the data from the Norwegian, Spanish, Turkish and Cyprus networks needed special treatment. Common ragweed is sparse in these regions and in most cases *Ambrosia* pollen – if present – is grouped together with pollen from other members of the Asteraceae family. If the annual pollen integral from the Asteraceae group was near zero then data from these sites were included as being without presence of *Ambrosia* pollen. Pollen stations with a low Asteraceae pollen integral during the ragweed flowering period were also included, while stations with a large Asteraceae pollen integral were excluded from the study.

The number of ragweed habitats for each grid cell within a 30 km radius of the pollen monitoring site was calculated using the function *focal statistics* provided with *Spatial Analyst Tools*, which is an extension to ArcGIS. These values (henceforth amount of habitats) were then extracted for the pollen monitoring sites. This is done simultaneously for all sites using the function *Extract values to point* also found within *Spatial Analyst Tools*. This approach by combining tools within *Spatial Analyst Tools* has shown to be much more computationally efficient for continental scale calculations as compared to previous approaches that have mainly been applied at the country level (Bonini et al., 2017; Karrer et al., 2015). This previous approach handled the sites individually and operated with the data in shape-file format (Skjøth et al., 2010; Thibaudon et al., 2014). The ragweed infestation level is then calculated at each site according to Thibaudon et al. (2014) and interpolated to the entire area of investigation, where the infestation level varies from 0% to 100%. The final gridded ragweed inventory was calculated at 1 km grid resolution by multiplying the gridded habitat map with the calculated infestation level. The 1 km grid was aggregated to 10 km (Fig. 3A) for comparison with plant density data. The sensitivity of the gridded data was tested by cross validation and displayed as a scatter plot (Fig. 3B) and geographically on a map (Fig. 3C) according to the recommendations by US-EPA (US-EPA, 2004). The 10 km inventory is discussed at the European level, while the higher detailed 1 km inventory is explored for selected areas and compared with the 10 km inventory (Fig. 4A to D). Both European inventories given with the 10 km and the 1 km grid are provided as supplementary information in form of tif files, which enables easy application of the data by authorities, forecasters and other users.

2.2. Inventories of plant density for Austria and Serbia and their comparison with the pollen-based inventory

Two plant density maps were produced for Austria (Karrer et al., 2015) and Serbia (Vrbničanin et al., 2008) based on unified nation-wide observation campaigns on the presence, absence and abundance classes of common ragweed for the same period as the pollen data (previous section). These data included areas with both widespread infestations of permanent populations of common ragweed and areas where the plant was absent. The data from Vrbničanin et al. (2008) were delivered as a 3-level categorical dataset of infestation of common ragweed with 10 km × 10 km resolution covering all of Serbia. The data from Austria were raw observational values of the presence/absence of common ragweed (Karrer et al., 2015). The datasets were converted into point-based shape files by calculating presence/absence on a 10 km × 10 km grid covering both countries. The density of presence (grid points) within a 30 km zone is then calculated for both Austria and Serbia at a 10 km resolution, i.e. the same distance and resolution used for the pollen based inventory. This enabled the data to be gridded in the same way as the pollen based inventory. The plant density maps were combined for both countries (Fig. 5A) and individual numbers in

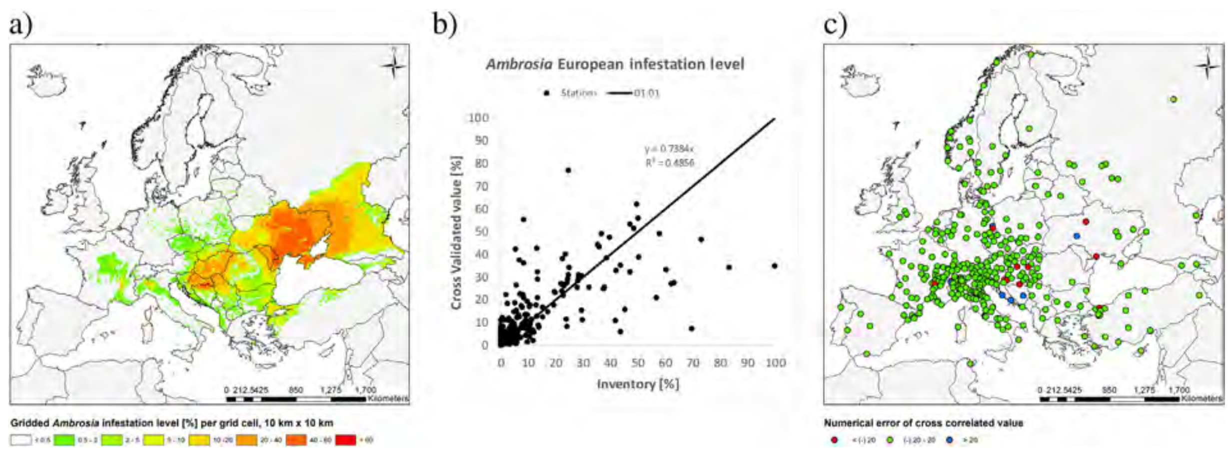

Fig. 3. A: Infestation [%] of *Ambrosia* in Europe combining airborne *Ambrosia* pollen data with land cover and elevation filter, aggregated to 10 km × 10 km. **B**: Cross validation at each point using the geographical distribution. **C**: Scatter plot showing cross validation results incorporating all sites in the study.

the grid cells were directly compared using linear correlation analysis (Fig. 5B).

3. Results

3.1. The pollen based ragweed inventory and its accuracy assessment

A total of 349 pollen monitoring sites were included in the study (Fig. 2B). A high density of stations was found in Italy, France and Hungary while a low density of stations was found in Romania, Moldavia parts of Russia and Turkey. The geographical locations and the overall pollen integral used in the calculation were stored within a point-based shapefile that also includes metadata with a citation for each dataset. This shapefile is available as supplementary information. The Rhône Valley, Northern Italy, the Pannonian Plain, parts of Turkey, most of Ukraine, and parts of Russia were found to be the main areas with high pollen integrals. The highest ragweed infestation was found in Ukraine followed by Russia and the Pannonian Plain, which corresponded well with the highest pollen integrals that were found in Russia, Ukraine and Croatia. These areas (Fig. 3A) also contained the main invasion fronts towards the North (e.g. Poland, parts of Russia and Ukraine), while the southern invasion fronts were found in Turkey near the Black Sea coast, parts of Italy and parts of France.

Cross validation provided an overall R^2 value of 0.49 (Fig. 3B) and a correlation of 0.74 and RMSE of 10.2%. The mapping of the absolute error (Fig. 3C) revealed that nearly all sites had an absolute error of <20%, while a few had much larger errors. These uncertainties were mainly related to areas with low densities of stations such as part of Ukraine, or near invasion fronts like the transition from the western Balkans to the Adriatic coastline. The 10 km gridded dataset highlights well known areas of infestation such as the Rhône Valley in France (Fig. 4A) and parts of Ukraine and Turkey (Fig. 4C) along the Black Sea coast. More detail can be seen with the 1 km grid resolution, which displays narrow areas with a high infestation in Italy and France (Fig. 4B) and is associated with narrow valleys found near Roussillon, France, and part of the Alpine region in either southern Switzerland and northern Italy. The 1 km inventory is also highly detailed around the Black Sea (Fig. 4D). The most highly infested areas in Russia and Ukraine are arranged in an arc around the northern coast of the Black Sea (Fig. 4D), corresponding to the location of Odessa. This is a combined effect of homogeneous terrain with a very high density of agricultural land, i.e. a large number of potential ragweed habitats and a lower density of pollen stations compared to areas such as the Rhône Valley in France. This is also the area with the highest uncertainty according to the cross correlation analysis.

3.2. The plant based inventory of common ragweed and its comparison with the pollen inventory

The re-calculated plant-based inventory for Serbia (Fig. 5A) identifies the northern part as being heavily infested, while the southern part contains notably less common ragweed. Similarly, the Austrian plant-based inventory shows high infestations around Vienna (Fig. 5A) and in the lowlands of the southern and eastern parts. Localised infestations, apparently in relation to major road networks expanding from the East to the West, are consistent with previous findings by Essl et al. (2009) and Vitalos and Karrer (2009). A substantial fraction of the country has low infestations coinciding with the Alpine region. The numerical comparison of the bottom-up plant-based inventory with the top-down pollen-based inventory provided a highly significant relationship ($r^2 = 0.64$ $P < 0.001$) (Fig. 5B).

4. Discussion

This study provides, to our knowledge, the first complete inventory of flowering ragweed all over Europe and western Asia showing both distribution and relative abundance. The inventory has been validated using both cross validation and two plant-based inventories for Austria and Serbia. The inventory substantially expands current methods used for developing top-down based inventories and provides an approach that is generally applicable both for ragweed as well as other anemophilous species. The new approach is demonstrably suitable across continents and due to its design it can at the same time incorporate several types of geographical data with varying detail along with other types of information. The new approach is, therefore, both flexible and made for either local or global implementation. The results show large variations in infestation levels throughout the European landscape – variations that, as far as we know, have not previously been identified. These variations are in part related to the regional distribution of ecosystems likely to be affected and partly associated with factors, such as steep terrain or specific agricultural management schemes, that suppress the level of ragweed invasion.

The inventory is a major synthesis from COST Action FA1203-SMARTER for the "Sustainable management of *Ambrosia artemisiifolia* in Europe" (Müller-Schärer et al., 2018); a large EU-funded network that operated from 2012 to 2016 with >250 active scientists from over 30 countries (Müller-Schärer et al., 2018). The data collected within SMARTER is, to the best of our knowledge, the largest amount of *Ambrosia* pollen data ever collected. The dataset includes information from English and non-English sources, thereby documenting ragweed infestations from regions not previously considered. The map of

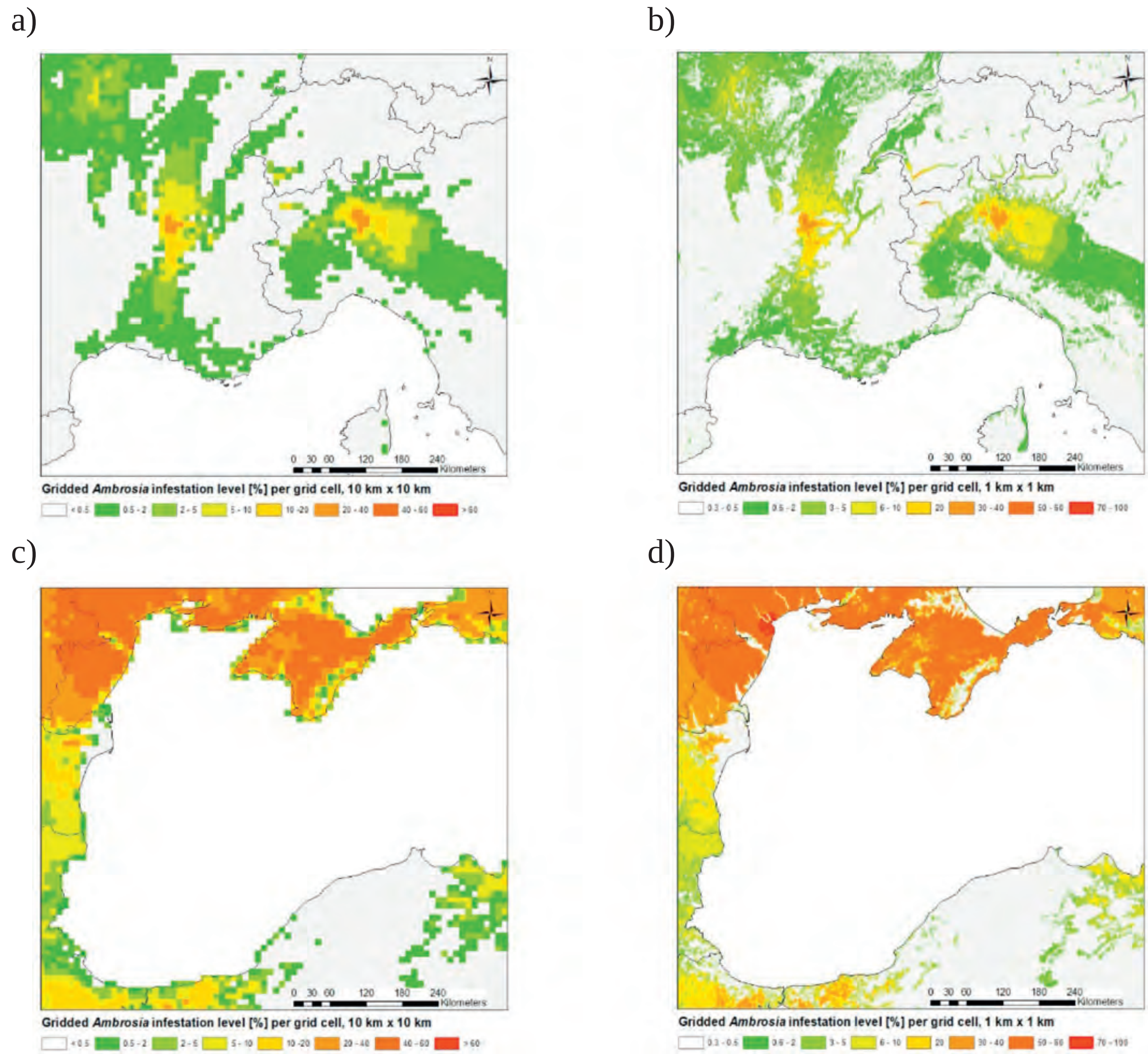

Fig. 4. A: Infestation level of *Ambrosia* pollen covering the Rhone valley and the Milan region at 10 km × 10 km. **B**: Infestation level of *Ambrosia* pollen covering the Rhone valley and the Milan region at 1 km × 1 km. **C**: Infestation level of *Ambrosia* pollen covering part of the Black Sea region and the coastal areas of Turkey, Bulgaria, Ukraine and Russia at 10 km × 10 km. **D**: 1 km × 1 km. Note the slightly different legends between 1 km and 10 km grid resolution.

ragweed abundance is also based on expert opinion, observations of plant abundances on the ground, and a mathematical approach for connecting and analysing the data. As such, this synthesis is arguably the most comprehensive and rigorous analysis of ragweed distribution and abundance ever considered for Europe.

The approach for generating these maps is applicable for other anemophilous plant species that release pollen to the air, to other periods of sampling, and other regions with different land cover types. The approach is not restricted to the use of pollen data analysed with optical microscopes, but can easily be applied to pollen data analysed with molecular techniques, thereby expanding the usefulness. Molecular approaches as well as approaches using optical microscopes, can provide volumetric measures of pollen that are in fact directly comparable (Müller-Germann et al., 2015). For instance, pollen and fungal pores collected with traps of the Hirst design (Hirst, 1952), which are used by many national networks, have been analysed using molecular approaches to produce time series of volumetric measures (Grinn-Gofroń et al., 2016; Núñez et al., 2017). In fact, nationwide monitoring for airborne grass pollen using molecular approaches has recently been demonstrated (Brennan et al., 2019). As such it is possible to calculate the pollen or spore integrals (Galán et al., 2017) using molecular techniques if the study involves standard or calibration curves (e.g. Müller-Germann et al., 2015). Furthermore, the dataset can cover full seasons, which is the main requirement when using molecular data for this mapping approach. The traditional analysis of aerobiological samples by an optical microscope is often limited in its ability to identify airborne pollen because pollen or fungal spores are aggregated into groups such as genus (e.g. *Betula*), family (e.g. Asteraceae) or even 'type' (e.g. *Taxus*-Cupressaceae type). On the other hand, molecular approaches can identify pollen or spores that are morphological identical to other species when analysed with a microscope such as the pollen from different members of the Poaceae family (Brennan et al., 2019;

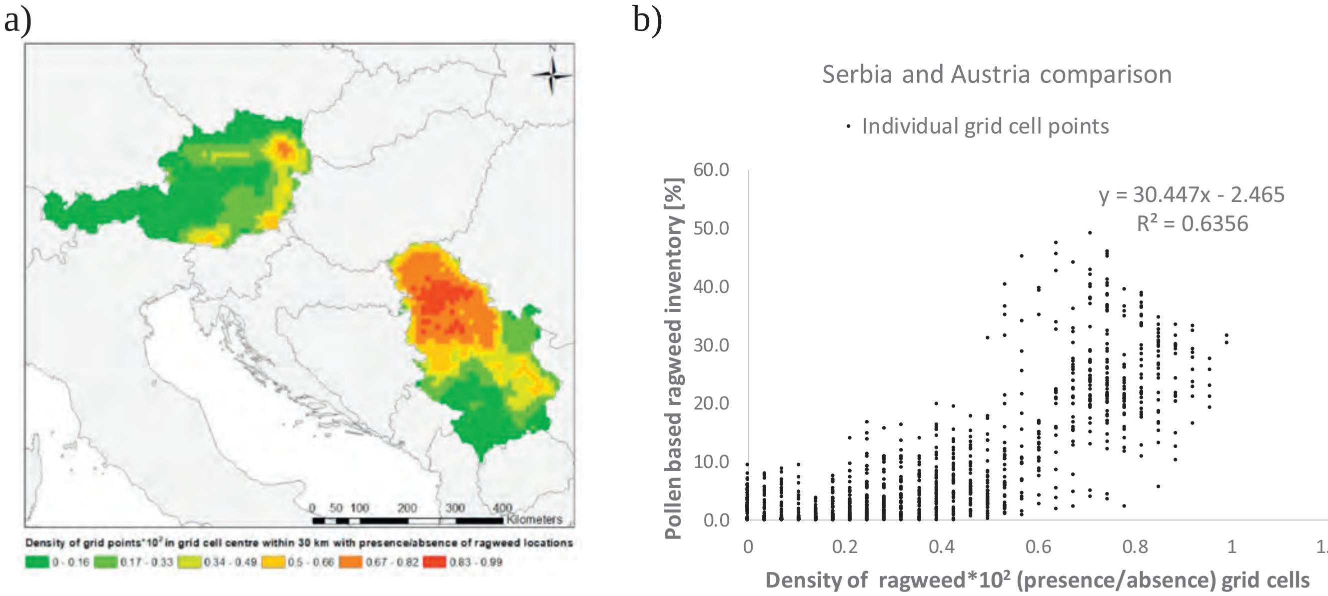

Fig. 5. A: Density of ragweed plants in Austria and Serbia based on unified nation-wide observation campaigns on the presence, absence and abundance classes of common ragweed for the same period as the pollen data, calculated using 10 km × 10 km grid cells. **B**: Scatter plot showing a comparison of the ragweed plant density map with corresponding grid cells from the pollen-based inventory.

Kraaijeveld et al., 2015), spores from the genus *Cladosporium* (Pashley et al., 2012) or pollen from *Ambrosia artemisiifolia* (Müller-Germann et al., 2017). The use of primers that either separate individual ragweed species or target individual species such as *Ambrosia artemisiifolia* (Müller-Germann et al., 2017) will provide substantial new insight into species diversity in the air and allow for studies into ecosystem behaviour or provide background data for management. These diagnostic methods would be particularly powerful when analysed spatially using the approach presented here. Pollen data are relatively simple to collect and so this approach is especially useful when the species under investigation are difficult and costly to map at larger spatial scales using other methods such as vegetation surveys or remote sensing (e.g. the global invader *Parthenium hysterophorus* or the highly allergenic species of *Parietaria judaica*). The background data and the final output data from this study are available in a well-established digitized form at several geographical resolutions (e.g. Fig. 4B and D). The inventory can, therefore, be easily updated and the data are available for planning mitigation strategies, scenario studies, and forecasting; including use by the atmospheric models used in the EU flagship Copernicus Programme. This enables substantial impact within and outside academia – a primary objective of the SMARTER network (Müller-Schärer et al., 2018).

The inventory presented here, thanks to the development of new methods, provides a substantial new understanding of the level of ragweed invasion across Europe that has not previously been identified. The inclusion of new regions, e.g. Turkey, provides a larger geographical coverage of ragweed infestation than previous studies conducted by Bullock et al. (2010), Prank et al. (2013) and Liu et al. (2016). Our inventory also shows much lower infestation levels in much of Northern Europe than these other studies, e.g. for northern Germany, Denmark, Belarus, the Baltic countries, Poland and Sweden. This is because the inventory reflects the fact that common ragweed is mainly found near settlements and that many regions in these countries are still free from common ragweed (Afonin et al., 2008; Grewling et al., 2016; McInnes et al., 2017; Sommer et al., 2015). The results suggest substantial spatial variations in infestation levels in key areas such as the Pannonian Plain and in countries like Italy. Our inventory shows almost no infestation in large parts of Italy and, as such, is in agreement with national assessments conducted by Celesti-Grapow et al. (2009) and Gentili et al. (2017). Attempts of ecosystem modelling conducted by Chapman et al. (2014) and Storkey et al. (2014) have some similarities with this study (e.g. in Russia and Ukraine), but also contain major differences in Northern countries (e.g. the UK, Germany and Denmark) as well as countries near to or on the Pannonian Plain (e.g. Romania, Bulgaria and the European part of Turkey). In our inventory, ragweed is hardly present in the Northern countries (McInnes et al., 2017), has either widespread but regional presence or patchy distribution in countries such as France and Germany (Buters et al., 2015; Zink et al., 2012), and is found abundantly in the European part of Turkey (Ozaslan et al., 2016) and along parts of the Black Sea coast (Onen et al., 2014). The approach implicitly assumes that each region with considerable and consistent amounts of ragweed pollen is predominantly influenced by local plants and that atmospheric processes keeping pollen airborne have similar effects throughout the model area. This is not necessarily the case, where a good example that can affect pollen dispersion is the height of the planetary boundary layer (Smith et al., 2008; de Weger et al., 2016). It has been shown that one of the important ragweed regions during the main ragweed season systematically contain higher planetary boundary layers compared to other European regions (Seidel et al., 2012). Nevertheless, the harmonised inventory presented in this study appears to agree considerably better with existing literature than large scale maps created in previous studies. This, combined with the cross validation and comparison with plant-based inventories, suggests that the approach presented in this study provides high quality inventories from a statistical point of view and is currently the most comprehensive method for estimating ragweed abundance throughout Europe.

5. Conclusion

In summary, the map of ragweed abundance presented here is, to our knowledge, the first complete assessment of ragweed invasion in Europe. Common ragweed is one of the most economically important invasive species in Europe and so is considered a flagship species. Mitigation is therefore highly needed. Our inventory can support successful mitigation strategies, both at national and international levels, such as the use of biological control or the implementation of new management schemes. As such, the inventory would need to be updated when major changes are seen in the distribution, thereby underlining the importance of long time series from pollen monitoring stations. Furthermore, the method produces superior results to other mapping approaches when used for pollen forecasting, where the objective is to enable hay fever sufferers to either reduce pollen exposure during high magnitude events or take medication. Finally, the mapping of ragweed in this way can be used to document the effect of climate change on vegetation as the northward expansion of common ragweed in Europe is currently limited by cooler climates. A main challenge with the approach has been in securing sufficient amounts of data on a continental scale and finding a method for handling regions with poorer data coverage. Overall, the approach shows the high value of pollen data, particularly when the data are applied to large spatial scales and combined with detailed land use maps and expert knowledge of plant distribution and ecology. Consequently, the production of inventories can help convince policy makers setting political and administrative actions against invasive species such as common ragweed.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.05.215.

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