Environment International 61 (2013) 115–126

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review

Common ragweed: A threat to environmental health in Europe

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ARTICLE INFO

Article history:
Received 1 April 2013
Accepted 13 August 2013
Available online 17 October 2013

Keywords:
Invasive alien species
Integrated weed management
Aerobiology
Species distribution
Aeroallergen

ABSTRACT

Common or short ragweed (*Ambrosia artemisiifolia* L.) is an annual herb belonging to the Asteraceae family that was described by Carl Linnaeus in the 18th century. It is a noxious invasive species that is an important weed in agriculture and a source of highly allergenic pollen. The importance placed on *A. artemisiifolia* is reflected by the number of international projects that have now been launched by the European Commission and the increasing number of publications being produced on this topic. This review paper examines existing knowledge about ragweed ecology, distribution and flowering phenology and the environmental health risk that this noxious plant poses in Europe. The paper also examines control measures used in the fight against it and state of the art methods for modelling atmospheric concentrations of this important aeroallergen. Common ragweed is an environmental health threat, not only in its native North America but also in many parts of the world where it has been introduced. In Europe, where the plant has now become naturalised and frequently forms part of the flora, the threat posed by ragweed has been identified and steps are being taken to reduce further geographical expansion and limit increases in population densities of the plant in order to protect the allergic population. This is particularly important when one considers possible range shifts, changes in flowering phenology and increases in the amount of pollen and allergenic potency that could be brought about by changes in climate.

Contents

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http://dx.doi.org/10.1016/j.envint.2013.08.005

1. Introduction

Common or short ragweed (*Ambrosia artemisiifolia* L.) is a herbaceous species belonging to the Asteraceae family that was described by Carl Linnaeus in the 18th century (Linnaeus, 1753) based on specimens from North America (Virginia). In the past, European botanists tended to focus their efforts on plants growing in natural rather than anthropogenic environments and as a result common ragweed had often been neglected. Common ragweed has recently increased in prominence as its ecological features, anemophilous pollination strategy, and allergenicity have made it an important agricultural weed (Basset and Crompton, 1975) as well as important threat to environmental health (Oswalt and Marshall, 2008).

Interest in ragweed in Europe became particularly evident in the first decade of the 21st century. The steady progression from first identifying the problem to searching for possible solutions as well as a switch in focus from the regional to the continental scale can be observed. Attempts to control the spread of ragweed and limit population densities of the plant have, until recently, been conducted at a national level. The importance placed on *A. artemisiifolia* is reflected by the number of international projects that have now been launched by the European Commission and the increasing number of publications being produced on this topic (Fig. 1). This is the first paper to thoroughly examine all aspects of the environmental health problem posed by ragweed. The review paper will examine known knowledge about ragweed ecology, distribution and flowering phenology and the environmental health risk that this noxious plant poses in Europe. This paper will also look at control measures used in the fight against common ragweed and state of the art methods for modelling atmospheric concentrations of this important aeroallergen.

2. Ecology

2.1. Description of the plant

Among *Ambrosia* species, only *A. maritima* L. is native to Europe (Laaidi and Laaidi, 1999; Laaidi et al., 2003; Meusel and Jäger, 1992). The other *Ambrosia* species distributed in Europe, *A. artemisiifolia* L. (=*Ambrosia elatior* L.), *Ambrosia trifida* L., *Ambrosia tenuifolia* Spreng. and *Ambrosia psilostachya* DC. (=*A. coronopifolia* Torr. & Gray) are native to North America and were introduced to Europe by agriculture product shipments, e.g. purple clover seeds (Makra et al., 2005), potatoes or maize (Chauvel et al., 2006). *A. artemisiifolia* is the most widespread ragweed species, and has expanded its distribution out of its native range to Europe (Chauvel et al., 2006), Asia (Xu et al., 2006), Australia (McFadyen, 1984), Africa and South America (http://www.q-bank.eu/Plants/BioloMICS.aspx?Table=Plants%20-%20Species&Rec=45&Fields=All). As such, it is the most important ragweed species in terms of allergy. Note that the term "ragweed" is often used in the subsequent text to describe common ragweed (*A. artemisiifolia*).

Common ragweed is an erect annual herb that grows up to 250 cm high with a taproot. The plant is characterised by a bushy-branched or unbranched hairy stem that bears compound pinnately lobed leaves with whitish nerves (Fig. 2A). Flowers are organized in heads containing either male flower or female flower (Fig. 2B). In the monoeceous common ragweed, the male heads contain staminate (pollen producing) flowers (10–150 or more flowers in each head) that are stalked, downward orientated and arranged in spike like clusters (raceme) at the tips of the primary stem and lateral branches. Female heads containing one or few pistillate (seed producing) flowers are sessile and situated in the axils of the leaves immediately below the staminate spikes. Some

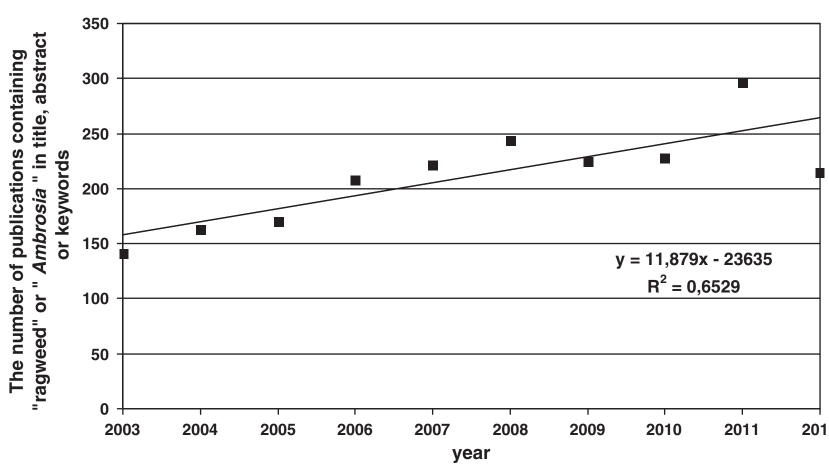

Fig. 1. The number of studies related to *A. artemisiifolia* published during the past 10 years, estimated by analysing the number of publications appearing in SCOPUS (www.scopus.com), which is the world's largest abstract and citation database of peer-reviewed publications. The number of annually published papers per country was extracted for the period 2003–2012. The search criterion was for the words "ragweed" or "*Ambrosia*" in the title, abstract or keywords. The database survey retrieved a total of 2112 publications containing the search criterion. These publications were linked to 70 countries worldwide. Note that, the majority (57.1%) of publications were linked to regions outside of the native range of *A. artemisiifolia*. 34.2% of publications came from Europe and 15.2% from Asia both considered threatened by *A. artemisiifolia* invasion. The number of published papers dealing with ragweed significantly increased over the last ten years (slope = 11.879, p = 0.005). Positive trend exists for all continents (Europe, Asia, North America, Latin America, Africa and Australia with Oceania). When compared separately, the slope of the trend was notably higher in Europe (slope = 5.388, p = 0.038) and Asia (slope = 3.194, p = 0.002) compared to the North America (slope = 1.394, p = 0.022). This survey suggests an increased awareness about the invasive potential of *A. artemisiifolia* outside of its native range.

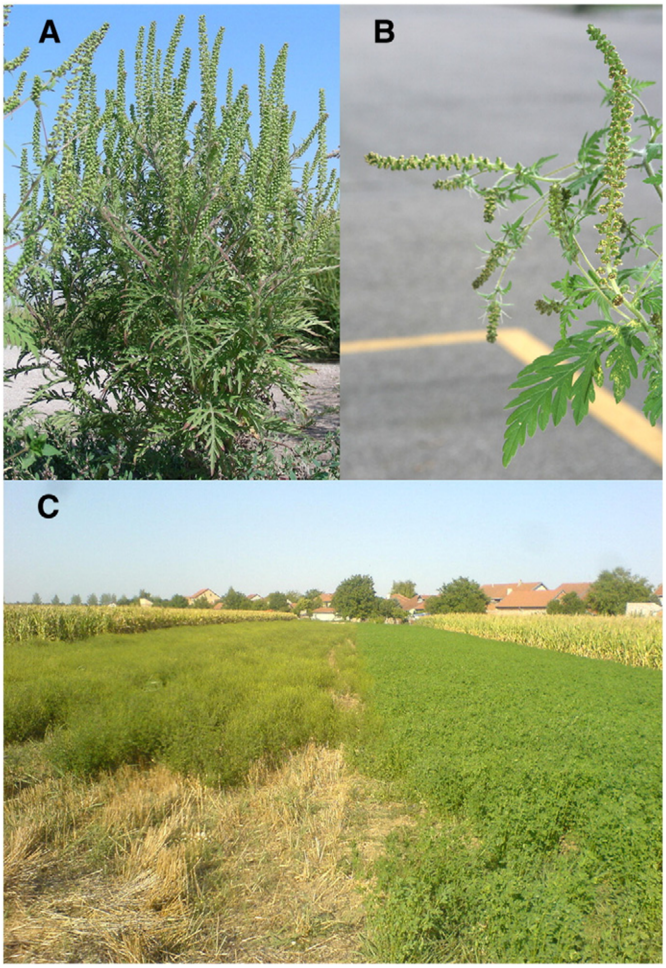

Fig. 2. (A) Typical branched habit of *A. artemisiifolia* on ruderal places in Austria; (B) *A. artemisiifolia* plant showing the male flowers (inflorescences) and pollen clumps released on the leaf surface. The image was taken in Denmark near to Copenhagen, showing the northward progression of the plant. (C) A field covered by a large *A. artemisiifolia* population after the harvest of winter wheat (left hand side). Image taken on the Pannonian Plain (Serbia), which is one of the most infected regions in Europe.

individuals may only bear female flowers, even in the position of the commonly male heads of the terminal spikes (Kazinczi et al., 2008a; McKone and Tonkyn, 1986). After fertilization, a woody 2.5 × 3.5 mm fruit (syconium, achene), bearing one seed is developed (Basset and Crompton, 1975). It is important to emphasize the strong variability in size, leaf shape, inflorescence form, and degree of hairiness that can lead to misidentification. Seedlings and small vegetative plants can be particularly difficult to recognize, and species where possible misidentification can occur include other *Ambrosia* (e.g. *A. trifida* L. and *A. psilostachya*), other genera of the Asteraceae family (e.g. *Artemisia*, *Tagetes*, *Senecio* and *Tanacetum*) as well as plants belonging to other families, especially plants with pinnately lobed leaves (Buttenschøn et al., 2009). A number of ecotypes are recognized in common ragweed (Dickerson and Sweet, 1971), and particular attention should be given to variability in plant biomass (Leskovsek et al., 2012), which shows strong positive corelation to the number of flowers per plant and thus pollen and seed production (Fumanal et al., 2007; Paquin and Aarssen, 2004).

2.2. Requirements for growth and spread

Common ragweed is a rather plastic ("polymorphic" or "highly variable") species that predominates in the early stages of vegetation development (Maryushkina, 1991). A warm continental climate and deep soils favour the growth of the plant and it can colonise a wide range of habitats (Fumanal et al., 2008b), such as cultivated fields, disturbed grasslands and roadsides as well as riparian and ruderal habitats, if two conditions are fulfilled: (1) seed availability and (2) soil disturbance (Skjøth et al., 2010). The biological features of common ragweed and the ability of the species to spread quickly to habitats associated with frequent and extensive disturbance regimes that primarily result from human activities, makes it an important agricultural weed that can potentially compete with annual crops for resources (Dahl et al., 1999; Janjić et al., 2007; Kazinczi et al., 2008a; Makra et al., 2005; Maryushkina, 1991; Peternel et al., 2005; Saar et al., 2000; Taramaracaz et al., 2005). For instance, losses between 4% and 22% have been observed in white bean fields, where the loss is determined by the development of the crop in comparison to ragweed (Chikoye et al., 1995). Ragweed is not considered a major problem in wheat with respect to crop production, but it can easily emerge at the fields after winter wheat harvest (Mutch et al., 2003) developing large populations (Fig. 2C).

Ragweed's ability to successfully colonise new areas is often attributed to the potential to produce viable seeds after self-pollination (Basset and Crompton, 1975). Population genetic studies (Gaudeul et al., 2011; Gladieux et al., 2011; Karrer, 2012) indicate significant heterozygosity deficits following partial self pollination. This would allow even single ragweed individuals to overcome population genetic bottlenecks during colonisation. On the other hand, a recent experimental study demonstrated that successful fertilization in *A. artemisiifolia* requires crossing of the gametes from different individuals (Friedman and Barrett, 2008). The latter is a disadvantage for successful colonisation but it is apparently overcome by high seed production and ability to survive unfavourable conditions in dormant seed banks.

Each common ragweed plant can produce from about 3000 to 62,000 seeds (Dickerson and Sweet, 1971) that can remain dormant for at least 39 years if conditions are unsuitable for germination (Basset and Crompton, 1975). A recent study in France found large amounts of viable seeds down to a depth of 20 cm in the soil (Fumanal et al., 2008a). The growth and phenological development of common ragweed depends on both temperature and photoperiod (Allard, 1945; Deen et al., 1998) and so the geographical distribution of common ragweed is limited by climate. The plant's biology determines the limits of its geographical distribution. For common ragweed it was previously believed to be between latitudes 45° and 30°, both north and south (Allard, 1943). However, in Europe all major naturalised populations (Rhône Valley, Po Valley, Pannonian Plain and Ukraine) are found either around, or to the north, of 45°N. The growing season is too short for seed maturation at higher latitudes and areas of high elevation (Allard, 1945). But in Europe, some naturalised populations persist even at 52°N (east of Berlin; Starfinger, 2008). Ragweed is termed a short-day plant because flowering is initiated by a shortening length of day. Like other short-day plants, generative development in ragweed starts with the decrease of day-length but temperature is important factor that governs this process (Allard, 1945). Low spring temperatures cause a delay in germination, which could mean that there is insufficient vegetative development before generative growth is induced, although Kazinczi et al. (2008a) described how cohorts that germinated later in the year needed fewer days for flowering to commence. A short summer also shortens the period when there is sufficient heat for the completion of generative growth, in particular seed maturation, and so the plant cannot become naturalised. A maritime climate also seems to limit the spread of the plant (Comtois, 1998). Ragweed seeds require moist chilling (stratification) before they can germinate (Baskin and Baskin, 1977, 1980; Pickett and Baskin, 1973; Willemsen, 1975). This stratification is less likely in temperate maritime climates where winters are mild and without notable temperature fluctuations (Pickett and Baskin, 1973), and so this could be a limiting factor for the development of large and stable populations of ragweed in these areas. It should be noted, however, that ragweed plants can still be present as casual populations where seeds are introduced from outside sources, but plants will not necessarily flower or set seed where conditions are not favourable.

It is interesting to note that chamber studies have shown that *A. artemisiifolia* has the ability to take-up significant quantities of soil Pb (Pichtel et al., 2000). This feature, together with its high growth rate, biomass production and preference to disturbed habitats, makes common ragweed a suitable candidate for soil phytoremediation (Ong et al., 2008).

2.3. History of ragweed in Europe

Changes in agricultural practices during the last century, particularly a change towards more intensive farming systems, provided a mechanism for accelerated expansion in the distribution and abundance of invasive weeds. With respect to this, Kiss and Béres (2006) emphasized the importance of the major socio-economic processes that tend to increase the area of disturbed land, in the massive spread of ragweed in various parts of the world. By analysing pollen deposits, palaeoecological studies recorded the presence of ragweeds in the North American flora as far back as late Pliocene (Davis and Moutoux, 1998). Notable increases in ragweed pollen in sediment are a marker of chronic soil disturbance, related to either climate change driven drought stress, erosion and fires (~9500 years ago) (Faison et al., 2006), or land clearance associated with the arrival of Europeans (~200 years ago) (Fuller, 1997). Ragweed populations growing on agricultural land are notable sources of seeds and pollen, even though studies have shown that ragweed plants growing within crop fields (i.e. corn, soybean) produce less pollen and seeds compared to those growing on bare habitats (Simard and Benoit, 2012).

The presence of ragweed in a particular region is positively correlated with the length of time passed since its introduction (Chauvel et al., 2006). According to herbarium records the ragweed invasion was already underway in 1863 in France (Chauvel et al., 2006), 1902 in Italy (Mandrioli et al., 1998) and 1907 in the Pannonian part of Romania (Csontos et al., 2010). As a result, the Rhône Valley (France), parts of Northern Italy and the Pannonian Plain, predominantly Hungary (Apatini et al., 2008; Járai-Komlódi, 2000; Járai-Komlódi and Juhász, 1993; Juhász et al., 2004; Vitányi et al., 2003) but also parts of Austria (Jäger, 2000), Bosnia and Herzegovina (Janjić et al., 2007), Croatia (Juhász et al., 2004; Peternel et al., 2005), Czech Republic (Rybníček et al., 2000), Romania (Juhász et al., 2004), Russia (Reznik, 2009), Serbia (Janjić et al., 2007; Juhász et al., 2004; Šikoparija et al., 2006), Slovakia (Bartková-Scevková, 2003; Makovcová et al., 1998), Slovenia (Juhász et al., 2004; Seliger, 1998) and Ukraine (Mosyakin and Yavorska, 2002), are considered to be the most important sources of ragweed pollen in Europe (Rybníček and Jäger, 2001). Common ragweed has been found as far north as Sweden (Dahl et al., 1999) and recent investigations show a consistent increase in ragweed pollen load in another Baltic country, Lithuania, despite the fact that the number of ragweed plants has not increased (Šaulienė and Veriankaitė, 2012). Šaulienė and Veriankaitė (2012) showed that ragweed pollen was predominantly recorded in Lithuania when winds were from the south-east, suggesting that ragweed could be expanding its abundance to the south of the country where it is already established.

2.4. Ragweed as a pest in agriculture and natural ecosystems

The European and Mediterranean Plant Protection Organization (Brunel et al., 2010) has considered common ragweed to be an invasive alien plant since 2004, but not as a pest organism — grading it as a lower priority. However, ragweed is known as a serious agricultural weed in the Pannonian Plain (Karrer, 2012; Kazinczi et al., 2008b), Eastern Europe (Russia, Ukraine) and in parts of the Rhône Valley (France) (Chauvel and Cadet, 2011). In Hungary, ragweed is already ranked top within the national list of arable weeds (Novák et al., 2009) and in Russia it is listed as a quarantine organism (Savotikov and Smetnik, 1995). Regulations and control activities against living ragweed plants are to be applied by law in Switzerland and Hungary.

Crops with close a taxonomical relationship with *Ambrosia*, such as sunflower, which make chemical control unsuitable and the degree of soil disturbance in common agricultural praxis (e.g. spaced sown corn is more suitable for ragweed infestation compared to densely sown wheat) determine the susceptibility of a particular crop to ragweed infestation. These factors also influence the effects of ragweed infestation. It can be argued that any loss due to weeds is unacceptable, but a single-year yield loss of 5 or 10% is often required for the treatment cost to become cost effective (Clay et al., 2006). For instance, losses between 4% and 22% have been observed in white bean fields, where the loss is determined by the development of the crop in comparison to ragweed (Chikoye et al., 1995). If the weed population is high, the yield loss in soybean (compared to estimated weed-free yield) could reach 75% per weed plant (Cowbrough et al., 2003) while in corn it can go as high as 80.1% per weed plant (Weaver, 2001). However, the later study showed that common ragweed was more competitive with soybean than with corn (Weaver, 2001). *A. artemisiifolia* is not just an agricultural pest, but it is also recognized as an invader of natural ecosystems such as grasslands, where it has been suggested that its abundance is negatively related with species diversity and pastoral value (Sărăţeanu et al., 2010). Allelopathic interactions of *A. artemisiifolia* with neighbouring plants (mostly crops) are known (Csiszár et al., 2013; Jackson and Willemsen, 1976) but their functionality in the field is not understood or experimentally tested in natural ecosystems up to now.

3. Ragweed flowering phenology

3.1. Seasonal development of flowers and pollen production

The development of flowers in common ragweed starts after the summer solstice and continues as long as the length of day is above the critical length required for induction of flowering (Allard, 1945). Male flowers are developed several days before female flowers (Deen et al., 1998). Longer days are favourable for development of male flowers while shorter days are favourable for development of female flowers so plants that emerged late in the year sometimes fail to develop male flowers due to insufficient length of the day (Allard, 1945). Flower maturation and flowering are not simultaneous on a single plant. Male flower heads mature sequentially from the base to the top of the tips of the primary stem and lateral branches (Payne, 1963) resulting in longer pollen anthesis of the single plant. In Europe, common ragweed typically flowers from July to October (Kazinczi et al., 2008a).

Common ragweed is an anemophilous (wind pollinated) plant. For anemophily to be successful a high number of pollen grains released by pollinating plants must reach conspecific individuals downwind (Whitehead, 1983). As a result, anemophilous species are characterised by high pollen production to compensate for the fact that the bulk of the grains is lost, and morphological adaptations that help the release (i.e. exposed anthers) and dispersion of pollen (Faegri and Iversen, 1992; Whitehead, 1983).

As a result of adaptation to wind pollination strategy, ragweeds possess one of the most highly modified inflorescence types found in the Asteraceae (Payne, 1963). Each ragweed plant produces millions of pollen grains that are small (18–22 μm) and contain small air chambers between layers of the outer pollen wall, which is unique in the Asteraceae plant family (Payne, 1963). As a result, ragweed pollen can readily become airborne when conditions are favourable (Cecchi et al., 2006; Comtois, 1998; Dahl et al., 1999; Fumanal et al., 2007; Smith et al., 2008; Stach et al., 2007; Taramaracaz et al., 2005). On average, total annual pollen production of ragweed plants has been estimated as 1.19 ± 0.14 billion pollen grains (Fumanal et al., 2007) but various environmental conditions (Rogers et al., 2006; Simard and Benoit, 2011, 2012) could alter plant fitness resulting change in pollen production.

3.2. Pollen release mechanisms and diurnal patterns

Ragweed pollen and flower morphology indicates that anemophily was a secondary development from entomophilous (insect pollinated) ancestors. Ragweed pollen is released in clumps (Martin et al., 2009) that tend to fall and adhere to surrounding vegetation (Bianchi et al., 1959) so emission of pollen often results from the resuspension processes. Like other wind pollinated plants from the Asteraceae family (i.e. *Artemisia vulgaris*, *Iva xanthifolia*, and *Xanthium strumarium*) the surface of ragweed pollen is covered in short spines (Fig. 3), which are reduced in length compared to typical entomophilous species (e.g. *Helianthus annuus*) that are strongly sculptured (Faegri and Iversen, 1992).

There is a definite diurnal periodicity in common ragweed flowering, with the extension and opening of the anthers occurring between 06:30 and 08:00, which correlates with a rise in temperature and reduction of relative humidity (Bianchi et al., 1959). Peak concentrations of ragweed pollen have been reported from approximately 06:30 to around midday in field studies where the sampler was located in the centre of plots of ragweed at a height of 0.1–0.5 m above the plants (Ogden et al., 1969).

3.3. Impact of atmospheric transport on pollen concentrations and aeroallergens

The time that the pollen is recorded will vary depending on the transport time (a product of distance and wind speed) from the source to the sampler. For example, in Burgundy peak diurnal concentrations attributed to a local source were recorded between 09:00 and 13:00 at several samplers situated at a similar height above the ground (Laaidi and Laaidi, 1999). This knowledge has been used to examine episodes of regional scale and long-distance transport of ragweed pollen and identify possible source areas (Cecchi et al., 2006; Kasprzyk et al., 2011; Šikoparija et al., 2009, 2013; Smith et al., 2008; Stach et al., 2007). Such episodes occur intermittently but the clinical impact of allergenic ragweed pollen arriving from distant sources remains unclear (Cecchi et al., 2010b). Although a recent study has found Amb a 1 in air samples collected in Poznań, Poland, during episodes of long-distance transport from the Pannonian Plain (Grewling et al., 2013).

Atmospheric concentrations of *Ambrosia* pollen are monitored across Europe by a network of sites using volumetric spore traps of the Hirst (1952) design. The spatial distribution of airborne pollen from the most important allergenic taxa in Europe has recently been described

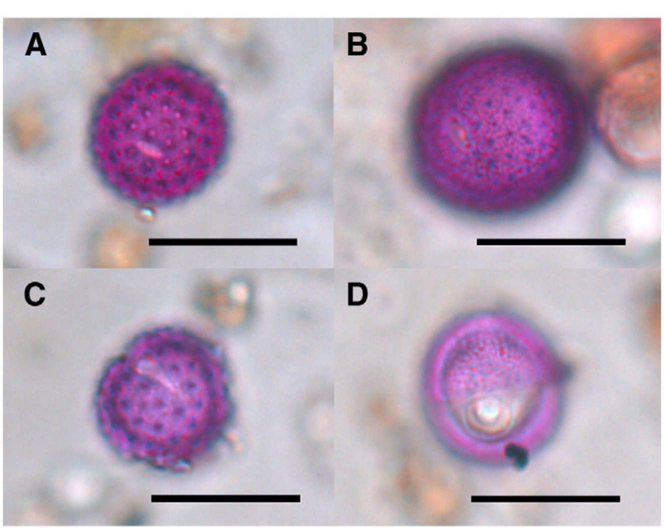

Fig. 3. Anemophilous Asteraceae pollen grains, isolated from aerobiological samples: (A) *Ambrosia*; (B) *Xanthium*; (C) *Iva*; (D) *Artemisia* (×400, scale bar 20 μm).

in a multi-author publication (Skjøth et al., 2013b) (Fig. 4). Pollen count data are considered a proxy for aeroallergen exposure, but it has been suggested that monitoring the allergens themselves together with pollen in ambient air might be an improvement in allergen exposure assessment (Buters et al., 2012). The recent EU funded HIALINE study (http://www.hialine.com/en/about.php) examined the atmospheric concentrations of the major allergens of birch (Bet v 1), grass (Phl p 5) and olive (Ole e 1) across Europe, but there has not been such an extensive systematic study examining airborne concentrations of ragweed pollen allergens in the source area and so this is a gap in current research.

4. The effects on health

4.1. Spatial and temporal trends in respiratory diseases due to ragweed

The first allergies to ragweed pollen were described as 'autumnal catarrh' by Dr. Morrill Wyman (1875) in the United States during the second half of the 19th century. Since then, ragweed pollen has become the second most important cause of seasonal asthma and rhinitis in many areas in the US (Salo et al., 2011; White and Bernstein, 2003) and Canada (Chan-Yeung et al., 2010) and its clinical relevance has dramatically increased even in Europe in the last decades (Burbach et al., 2009). Regional studies confirmed this trend: in Austria, it increased from 8.5% to 17.5% (Hemmer et al., 2011), and in the last decade it became the second most frequent cause of respiratory allergy around Milan (Northern Italy) (Asero, 2007).

In a recent multicentric European study on 3034 patients, more than 66% were sensitized to ragweed (Bousquet et al., 2009), although with remarkable differences between the countries. Sensitization rate of the allergic population goes from around 60% in Hungary (Makra et al., 2004) to 19.5% in Southern Bavaria (Ruëff et al., 2012) and it is virtually absent in certain biogeographical regions in Europe such as Mediterranean (e.g. Spain), Atlantic (e.g. UK) and Boreal (e.g. Sweden) (Bousqet et al., 2007).

Studies that specifically address public health and socioeconomic impacts of ragweed allergy are still lacking. However, direct and indirect costs can be estimated on the bases of prevalence of sensitization and allergy to ragweed. The cost of medication (direct costs) and loss of productivity/school days (indirect costs) for pollen-induced asthma and rhinitis were recently published in a EU report (A.A.V.V. Assessing and controlling the spread and the effects of common ragweed in Europe. Final report: ENV.B2/ETU/2010/0037. 2013; 128–140).

4.2. Major allergens in ragweed and cross-reactivity

The threshold value for clinical symptoms is below 20 ragweed pollen grains/m^3 (Comtois, 1998; de Weger et al., 2013; Jäger, 1998, 2000; Taramaracaz et al., 2005) and ragweed pollen is recognized as highly allergenic. The major allergen in ragweed pollen, Amb a 1, a 38-kDa non-glycosylated protein that belongs to the family of pectatelyase proteins, is a highly allergenic molecule that is recognized by 90% of ragweed-sensitized individuals (Gadermaier et al., 2008); therefore Amb a 1 is considered to be a good marker for specific ragweed sensitization. Minor allergens, Amb a 5 (group 5 allergen), Amb a 6 (LTP family) and panallergens Amb a 8 (profilin), Amb a 9 and 10 (polcalcins) have been also identified so far (www.allergome.org — accessed 21 August 2012).

A recent study identified the presence of allergenic terpenoids in common ragweed pollen grains (Taglialatela-Scafati et al., 2012). These secondary metabolites are known to induce potent inflammatory responses and therefore can enhance the sensitizing properties of the allergenic proteins of *Ambrosia* pollen grains.

In areas with co-exposure to pollen of *Ambrosia* and *Artemisia*, both belonging to the Asteraceae family, concomitant sensitization and clinical reactivity to either weed pollen have been observed (Hirschwehr et al., 1998), making identification of primary sensitizing allergen

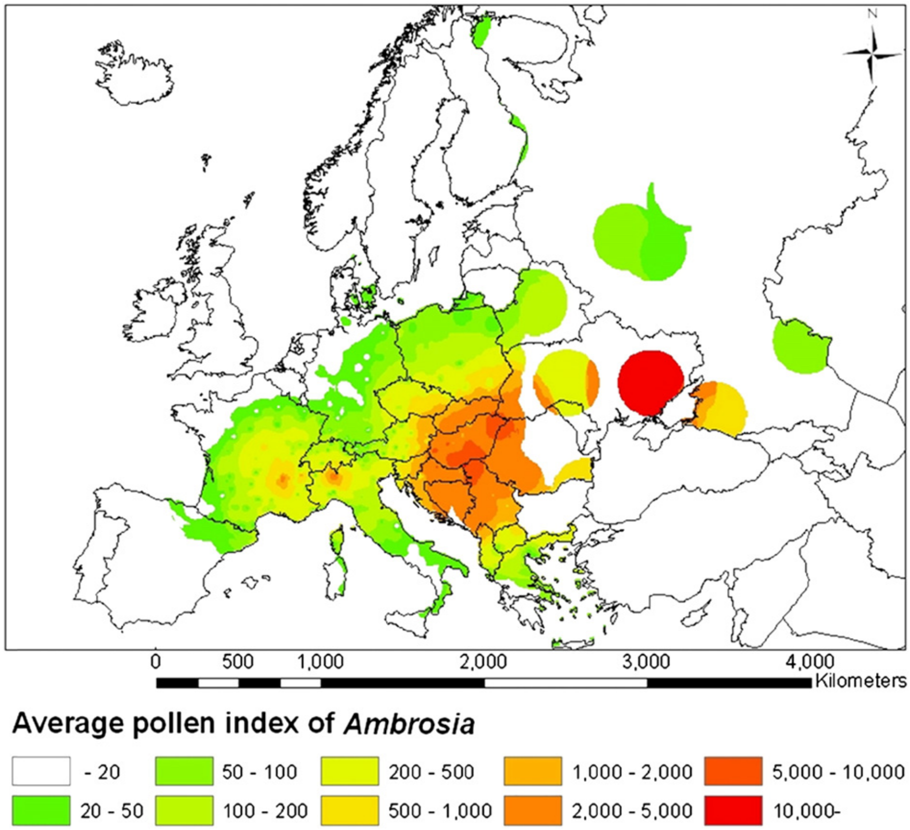

Fig. 4. A spatial assessment of the density of naturalised *Ambrosia* populations with flowering potential. The map is based on the mean annual pollen index of *Ambrosia* from 368 stations in Europe, simple interpolation, buffer zones of 200 km and presence/absence information in Flora Europea. Taken from Skjøth et al. (2013b). The map is based on data stored in the European Aeroallergen Network database (https://ean.polleninfo.eu/Ean/), which is the largest collection of *Ambrosia* pollen observations. It has a high station coverage in all of Europe, except for parts of Eastern Europe, which causes problems for mapping over countries like Belarus, Russia and Ukraine.

source by using pollen extracts difficult. Amb a 1 has been identified as a candidate molecule for causing this cross-reactivity, because of its high homology (65% amino acid sequence identity and 85% amino acid similarity) with Art v 6, a minor *Artemisia* allergen (Asero et al., 2006; Wopfner et al., 2005). More recent findings showed that Amb a 1 dominates the cross-reactivity with Art v 6 in terms of immune response although the latter can act as primary sensitizing allergen and facilitate sensitization to Amb a 1 (Jahn-Schmid et al., 2012).

4.3. Toxicity to animals and humans

The authors are not aware of any studies concerning *Ambrosia* toxicity to humans. Many kinds of metabolites including sesquiterpene lactones (e.g. ambrosin) and triterpenoid and caffeic acid derivatives have been isolated and identified from *A. artemisiifolia* (Bloszyk et al., 1992; David et al., 1999; Porter and Mabry, 1969; Tamura et al., 2004). The maximum content of these substances is retrieved in the budding and flowering stage (Parkhomenko et al., 2005). The constituents of the *A. artemisiifolia* herb and its essential oil make them significant bactericidal and fungicidal agents (Chalchat et al., 2004) and moderate antioxidants (Maksimović, 2008). Even the acetone extract of pollen contains ambrosin and artesovin, resulting in notable bacteriostatic and bactericidal properties (Solujić et al., 2008). It is interesting to note that lactones (in particular ambrosin) from acetone and water extracts of *A. artemisiifolia* pollen also showed genotoxicity in *Drosophila melanogaster* (Matic et al., 2008).

There is no evidence that *A. artemisiifolia* produces secondary metabolites that cause clinical intoxications in livestock (EFSA, 2010). However, ragweed tends to accumulate nitrates (Knight and Walter, 2001) that are reduced to nitrite in the gastrointestinal tract in ruminants, resulting poisoning. Studies on the performance of grazing sheep and goats on pastures contaminated with common ragweed indicated that although goats consumed more ragweed than sheep it does not appear that ragweed was a forb (a herbaceous flowering plant other than a grass) that was highly preferred or averted compared with others available in these pastures (Animut et al., 2005).

5. Climate change

Global average surface temperatures have increased by about 0.7 °C over the past hundred years (1906–2005) (Solomon et al., 2007). There is high confidence about a trend in many regions towards earlier greening of vegetation in the spring (based on Normalised Difference Vegetation Index derived from satellite images) linked to longer thermal growing seasons due to recent warming (IPCC, 2007). A number of studies have shown that the phenology (timing) of events, such as breeding or blooming, has become earlier (Ahas et al., 2002; Fitter and Fitter, 2002; Parmesan and Yohe, 2003; Root et al., 2003). Warming has been slightly greater in the winter hemisphere and changes in spring phenophases are more pronounced than those that occur in summer and autumn (Aasa et al., 2004; Ahas et al., 2002; Bertin, 2008; Fitter and Fitter, 2002; Solomon et al., 2007; Walther et al., 2002).

The effects of climate change on plant distribution can be summarised as: (1) general range shifts; and (2) invasions by species such as ragweed (Walther et al., 2002). Plant species are expected to undertake spatial (poleward and upward) shifts in ranges (IPCC, 2007) that will influence the abundance and distribution of allergenic plants (Cecchi et al., 2010a), and it is suggested that warming will promote the further spread and the invasive potential of *A. artemisiifolia* in Europe (Cunze et al., 2013). Increases in the abundance of anemophilous plants inevitably leads to increase in emission of their pollen in the atmosphere and can affect the exposure of the population to aeroallergens and increase sensitization (Asero, 2002; Confalonieri et al., 2007). The introduction of new invasive plant species with highly allergenic pollen also represents a risk to health (Confalonieri et al., 2007).

Rogers et al. (2006) showed that ragweed plants released from dormancy earlier in spring accumulated more resources through the season, which increased biomass reproductive effort and resulted in 54.8% more pollen production compared to those released from dormancy 30 days later. Increased temperatures during summer and early autumn could result in increased vegetative growth and the development of staminate flowers, and in so doing increase pollen production. These effects on flowering and phenology have also been observed in the differences between plants grown in urban and rural environments (Ziska, 2002; Ziska et al., 2003, 2008) as well as in the long term monitoring networks on continental scale (Ziska et al., 2011). However, the influence of photoperiod could mean that seeds will not ripen before temperatures decrease (Allard, 1932; Deen et al., 2001), and thereby impact on the plants ability to become naturalised.

In addition, increased concentrations of atmospheric CO_2 affect plant growth (Ziska and Caulfield, 2000), and so plants grown in higher concentrations of CO_2 generally develop faster, are larger at maturity and produce more pollen (Wayne et al., 2002; Ziska and Caulfield, 2000). Rogers et al. (2006) also showed that ragweed plants released from dormancy later, but grown in elevated levels of CO_2, had increased biomass and pollen production, which compensates for any disadvantages associated with a later start to the growing season. Recent findings confirm these earlier studies on the effects of anthropogenic factors on ragweed pollen allergenicity. Pollen collected in northern Italy from ragweed plants growing in urban parks and along high-traffic roads that are highly exposed to pollution produced pollen that was more allergenic than the pollen of plants from rural areas (Ghiani et al., 2012).

6. Control and modelling

6.1. Control actions

Control actions against common ragweed started in Eastern Europe due to it developing into a major weed there (Kazinczi et al., 2008a), a fact already recognized as early as the 1960s (Béres, 1981). The European Commission (EC) has recently supported a number of projects concerned with identifying and controlling the problem, which include:

- The EC 6th FP Project entitled “Delivering Alien Invasive Species Inventories for Europe” (DAISIE — http://www.europe-aliens.org) identified *A. artemisiifolia* as being one of the 13 plants listed among the 100 worst European invaders.
- Two national Pest Risk Analyses (PRAs) conducted for *Ambrosia* by Poland (EFSA, 2007a) and Lithuania (EFSA, 2007b) raised awareness of the scale of the ragweed problem in Europe, and scientific opinion about the presence of *Ambrosia* spp. seeds in animal feed and their effect on public health, animal health and the environment was provided by the European Food Safety Authority (EFSA) in 2010 (EFSA, 2010).
- In order to prevent new introductions and limit the expansion of the species' distribution, legislation restricting the amount of *Ambrosia* seeds in food containing whole grain and seeds (especially birdseed) has subsequently been adopted (EU, 2012).
- An 18 month EC (DG Environment) funded project “Assessing and controlling the spread and the effects of Common ragweed in Europe” commenced in March 2011 (http://www.ecnc.org/projects/ecosystem-services-and-biodiversity-assessment/common-ragweed-in-europe/). The objectives of this project included understanding the current extent of ragweed infestation in Europe, quantifying the direct and indirect effects on the economy, society and environment and developing measures to control the spread and introduction of ragweed (now and in future climates). The final output of this project is a 456 page report (https://circabc.europa.eu/sd/d/d1ad57e8-327c-4fdd-b908-dadd5b859eff/Final_Final_Report.pdf).
- In order to reduce the prevalence of *A. artemisiifolia* in Europe and reduce the burden on public health, agriculture and biodiversity the EC (DG Environment) launched “HALT AMBROSIA” (2011–2014). This project (http://www.halt-ambrosia.de/) examines non-chemical and integrated control strategies as well as the best use of herbicides.
- Added to this, the EUPHRESCO project “AMBROSIA” (http://www.euphresco.org/) published guidelines for the management of common ragweed and recommended an integrated approach based on best-bet control strategies (Buttenschøn et al., 2009).

Currently, control options are recommended at two levels (HALT AMBROSIA — www.halt-ambrosia.de): (1) Countries that lack naturalised populations have to disable any vectors that could introduce ragweed via contaminated crop seeds; (2) All countries that are already infested by naturalised ragweed populations should set up strict directives to control established populations that aim to prevent further spread at the local or regional scale, such as those already installed in Switzerland (Der_Schweizer_Bundesrat, 2008, 2010) and Hungary (Gólya et al., 2008).

Common ragweed is resistant to air and soil pollution (Pichtel et al., 2000; Ziska, 2002) and after damage such as defoliation and mowing it is still able to reproduce (Brandes and Nietzsche, 2006; Gard et al., 2013; Karrer and Pixner, 2012). Common ragweed can currently be controlled reasonably well in all major crops either by chemical (Kazinczi et al., 2008b) or mechanical or combined measures (e.g. Buttenschøn et al. (2009)) but has been shown to develop resistance to herbicides over time (Saint-Louis et al., 2005). Crop rotation and vegetation management are additional tools that can be used for ragweed control on arable fields and other heavily infected habitat types like roadsides (Kazinczi et al., 2008a; Milakovic and Karrer, 2010). More problematic, are short-term abandonment, inadequate chemical control and irregular disturbance rhythms (e.g. mowing), which all enable the development of persistent soil seed banks. Serious yield losses are mostly documented in crops like sunflower, soybean, oil pumpkin, red beans and potatoes because there are no effective control options currently available except for pulling up by hand. A serious problem arises from harvesters and mowers that transport tens of thousands of ragweed seeds from infected fields or roadside verges to areas that are not already infected (Karrer et al., 2012; Vitalos and Karrer, 2009). Thorough cleaning of machines after working in infested habitats is the first way to remove this problem (Der_Schweizer_Bundesrat, 2008, 2010).

The long-term control of common ragweed using biological measures (Fukano and Yahara, 2012; Gerber et al., 2011) is also to be evaluated by the EC Cooperation in Science and Technology (COST) Action FA1203 (2012–2016) entitled “Sustainable management of *Ambrosia artemisiifolia* in Europe” (http://www.cost.eu/domains_actions/fa/Actions/FA1203). COST “SMARTER” is in the Food and Agriculture domain and aims to coordinate institutions involved in *Ambrosia* research and management throughout Europe as well as provide a forum where experts who are already involved in the control of ragweed can discuss integration of management options with health care professionals, aerobiologists, economists, and atmospheric and agricultural modellers. The Action will make recommendations for the sustainable management of *Ambrosia* across Europe, and for monitoring its efficiency and cost effectiveness.

6.2. Living with ragweed

The EC has also examined the prospect of facing life with *Ambrosia*. The distribution (Skjøth et al., 2013b) and impact (de Weger et al., 2013) of ragweed pollen have been described in a multi-author publication that was brought about by COST Action ES0603 “Assessment of production, release, distribution and health impact of allergenic pollen in Europe" (EUPOL — http://www.unifi.it/COSTEupol/index.html) that ended in 2011. More recently (2011–2016) the "atopic diseases in changing climate, land use and air quality" project (ATOPICA — http://www.atopica.eu/) aims to assess the health risks resulting from severe environmental changes and design suitable adaptation policies, with focus on atopic patients. In addition, the "Novel Vaccines for Allergen-specific immunotherapy of Ragweed pollen Allergy" (NOVARA — http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_LANG=EN&PJ_RCN=11515327&pid=0&q=CA54DC8A76E0FA5BBC3BCB7B246CB683&type=sim) is a Marie Curie Fellowship (2010–2012) that focuses on engineering hypoallergenic major ragweed pollen allergen (Amb a 1) as a new vaccine candidate for allergen-specific immunotherapy.

6.3. Modelling

6.3.1. Modelling approaches

Terrestrial models that examine temporal and spatial changes in ragweed distribution using both the typical spreading mechanisms and traits for successful invasion have been developed (Essl et al., 2009; Küster et al., 2008; Vogl et al., 2008) and can be used to predict where control measures should be implemented in the future. Where the focus is on ragweed as a problematic aeroallergen there is a need to combine both terrestrial and atmospheric models (Table 1). Historically, ragweed pollen concentrations have been mainly simulated with site-dependent statistical models (Laaidi et al., 2003; Makra and Matyasovszky, 2011; Makra et al., 2011), but a number of studies have shown that it is important to take into account the spatial variations in both sources (Skjøth et al., 2010; Zink et al., 2012) and the atmospheric transport on a wide range of spatial scales (Makra and Palfi, 2007; Prtenjak et al., 2012; Šikoparija et al., 2013; Smith et al., 2008; Zemmer et al., 2012). The number of studies listed in Table 1 is rather limited and highlights the need for more studies on ragweed pollen that includes atmospheric transport models. The fact that ragweed is an important aeroallergen means that the environmental conditions required for the production, release and dispersal of ragweed pollen are well described (Bianchi et al., 1959; Deen et al., 1998; Martin et al., 2010; Prtenjak et al., 2012; Stefanic et al., 2005) and the process can thereby be predicted (Chaxel et al., 2012; Laaidi et al., 2003; Prank et al., 2012). A number of different atmospheric models have been developed that can be used to predict ragweed pollen concentrations and the description of ragweed dispersal seems mainly to be related to the description of the source and a proper choice of atmospheric model (Skjøth et al., 2010).

Table 1
Overview of ragweed studies in Europe, including: the model name and reference; information about the study where the model was used to examine the atmospherioc transport of ragweed pollen (the study area, the number of sites and study years); and the reference of the study. These studies have been presented in peer reviewed literature as well as presented at the 2nd International Ragweed Conference, Lyon, 2012. Furthermore, there is one additional study over USA concerning ragweed and dispersion models, which in this case was the CMAQ model (Efstathiou et al., 2011).

Model name + reference in study	Study area (sites = n) study years	Reference
Receptor models		
ACDEP (Skjøth et al., 2002)	Poland (n = 1) 1995–2005	Stach et al. (2007)
ACDEP (Skjøth et al., 2002)	Poland (n = 8) 2005	Smith et al. (2008)
ACDEP (Skjøth et al., 2002)	Serbia, Macedonia (n = 5) 2007	Šikoparija et al. (2009)
ACDEP (Skjøth et al., 2002)	Poland (n = 3) 1997–2009	Kasprzyk et al. (2011)
HYSPLIT_ver4 (Draxler and Rolph, 2003)	Italy (n = 2) 1999–2004	Cecchi et al. (2006)
HYSPLIT_ver4 (Draxler and Rolph, 2003)	Italy (n = 4) 1999–2004	Cecchi et al. (2007)
HYSPLIT_ver 4.8 (Draxler and Hess, 1998)	Greece, Hungary, Germany (n = 3) 1998–2002	Makra et al. (2010)
HYSPLIT ver 4.9 (ARL, 2011)	Turkey (n = 1) 2007	Zemmer et al. (2012)
HYSPLIT_ver4 (Draxler and Rolph, 2003)	Lithuania (n = 3) 2004–2009	Sauliene et al. (2011)
HYSPLIT (Draxler and Hess, 1998)	Hungary (n = 1) 1989–2003	Makra and Palfi (2007)
WRF-ARV (Skamarock and Weisman, 2009)	Croatia (n = 2) 2002–2009	Prtenjak et al. (2012)
HYSPLIT_ver4 (Draxler and Rolph, 2003)	Spain (n = 8), 1994–2010	Fernández-Llamazares et al. (2012)
Regional source based models		
DEHM (Frohn et al., 2002)	Poland, Serbia, Macedonia	Skjøth (2009)
COSMO-ART (Vogel et al., 2008)	Hungary, Austria, Czech Republic, Germany	Zink et al. (2012)
SILAM (Sofiev et al., 2006)	Central Europe	Prank et al. (2012)
CHIMERE (Bessagnet et al., 2008)	France	Chaxel et al. (2012)

6.3.2. Relevant spatial scales in modelling atmospheric concentrations of ragweed pollen

The choice of atmospheric models determines the spatial scale that can be investigated (Orlanski, 1975; Seinfeld and Pandis, 2006; Sofiev et al., 2013a). Here we use the rigid scale definitions described by Orlanski (1975) that was also adapted by the air quality modelling community within the COST Action 616 (Kallos, 1998):

- Microscale (0–2 km): e.g. OML (Olesen et al., 1992) and AERMOD (US-EPA, 2003). Currently only one study has been carried out with focus on *Ambrosia* pollen near Washington DC, USA (Chamecki et al., 2009).
- Meso-gamma (2–20 km): e.g. OML (Olesen et al., 1992), AERMOD (US-EPA, 2003) and in some cases also trajectory models (e.g. HYSPLIT (Draxler and Hess, 1998)) or particle dispersion models (e.g. Stohl et al. (2005)). Currently, one European study has been carried out on the meso-gamma scale using a high resolutions version (2 km) of the WRF model (Prtenjak et al., 2012).
- Meso-beta (20–200 km): This goes beyond the Gaussian approach (e.g. Olesen et al. (1992)). Appropriate model tools for ragweed simulations can be both Lagrangian (Lagrangian trajectory and particle dispersion models) and Eulerian type models such as COSMO-ART (Zink et al., 2012), SILAM (Prank et al., 2012), DEHM (Skjøth, 2009), CMAQ (Efstathiou et al., 2011) and CHIMERE (Chaxel et al., 2012).
- Meso-alfa (200–2000 km): Nearly all European studies at this scale examine the long distance transport episodes of ragweed pollen from either the Pannonian Plain (Cecchi et al., 2006, 2007; Šikoparija et al., 2009; Smith et al., 2008; Stach et al., 2007) or Ukraine (Kasprzyk et al., 2011; Zemmer et al., 2012) using trajectory models such as HYSPLIT.

Current research suggests that simulations need to cover the microscale and all three meso-scales. Concentrations near single plants can decrease from more than 1000 grains/m^3 to less than 100 grains/m^3 within 100 m (e.g. Fig. 1 in Skjøth et al. (2013a)) while recorded episodes of Long Distance Transport can cover large parts of Europe (Kasprzyk et al., 2011). This cannot be achieved at the present time by using one single model (Sofiev et al., 2013b). One solution could be to combine regional and local scale models as discussed by Hertel et al. (2006). This approach has been shown to be usable in both monitoring of air quality (Geels et al., 2012) as well as assessment and regulation studies (Hertel et al., 2013). As a suite of atmospheric models are already available, so the main requirement here is that the models have access to a sufficiently accurate description of the emission, i.e. location, timing and amount. The timing of the emission can be based on a combination of phenological models and the specific pollen release pattern for ragweed (Bianchi et al., 1959; Martin et al., 2010; Ogden et al., 1969). Source based Eulerian dispersion models (see Meso-beta models) are still in the developmental phase and performance is greatly affected by source data, which is a problem that has been commented on repeatedly for more than a decade (e.g. Russell and Dennis, 2000) and is particularly pertinent when discussing natural particles such as pollen (Siljamo et al., 2013). The magnitude of the source can be obtained from inventories, and methods for producing inventories suitable for input into regional scale models are being developed (Chapman et al., 2012; Sikoparija et al., 2012; Skjøth et al., 2010). However, there are currently no local scale inventories available, thus limiting the use of local scale models. This is clearly illustrated in Table 1 as the entire list of ragweed studies uses regional scale models. Possible approaches for developing these inventories include manual investigations or the use of dynamic ecosystem models or remote sensing.

7. Conclusions

Common ragweed is a noxious invasive species that is an important weed in agriculture and a source of highly allergenic pollen. It is an environmental health threat, not only in its native North America but also in many parts of the world where it has been introduced. In Europe, where the plant has now become naturalised and frequently forms part of the flora, the threat posed by ragweed has been identified and control actions have started to be implemented at the national and European levels to reduce the negative impact on the human population. This is particularly important when one considers possible range shifts, changes in flowering phenology and increases in the amount of pollen and allergenic potency that could be brought about by changes in climate.

Acknowledgements

We acknowledge support from EU COST Action FA1203 "Sustainable management of *Ambrosia artemisiifolia* in Europe" (SMARTER), http://www.ragweed.eu

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