OPINION PAPER

Cross-fertilizing weed science and plant invasion science to improve efficient management: a European challenge

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Abstract

Both weed science and plant invasion science deal with noxious plants. Yet, they have historically developed as two distinct research areas in Europe, with different target species, approaches and management aims, as well as with diverging institutions and researchers involved. We argue that the strengths of these two disciplines can be highly complementary in implementing management strategies and outline how synergies were created in an international, multidisciplinary project to develop efficient and sustainable management of common ragweed, *Ambrosia artemisiifolia*. Because this species has severe impacts on human health and is also a crop weed in large parts of Europe, common ragweed is one of the economically most important plant invaders in Europe. Our multidisciplinary approach combining expertise from weed science and plant invasion science allowed us (i) to develop a comprehensive plant demographic model to evaluate and compare management tools, such as optimal cutting regimes and biological control for different regions and habitat types, and (ii) to assess benefits and risks of biological control. It further (iii) showed ways to reconcile different stakeholder interests and management objectives (health versus crop yield), and (iv) led to an economic model to assess invader impact across actors and domains, and effectiveness of control measures. (v) It also led to design and implement management strategies in collaboration with the various stakeholder groups affected by noxious weeds, created training opportunities for early stage researchers in the sustainable management of noxious plants, and actively promoted improved decision making regarding the use of exotic biocontrol agents at the national and European level. We critically discuss our achievements and limitations, and list and discuss other potential Old World (Afro-Eurasian) target species that could benefit from applying such an integrative approach, as typical invasive alien plants are increasingly reported from crop fields and native crop weeds are invading adjacent non-crop land, thereby forming new source populations for further spread.

Keywords: integrated weed management, biological weed control, plant invasion, *Ambrosia artemisiifolia*, interdisciplinary and international research cooperation

Weed science vs. plant invasion science in Europe: different history and different focus with regard to management

Weed science has historically been most successful in providing efficient control of weeds by keeping up with modernization in agricultural practices (e.g. precision spraying and sophisticated machinery for mechanical weed control; Jordan, Schut, Graham, Barney, Childs et al. 2016) and by establishing close relationships with the private sector (Box 1). However, Fernandez-Quintanilla, Quadranti, Kudsk and Barberi (2008) recognized some important failures of weed science in modern European societies that resulted from the close ties to agriculture, such as soil and water degradation, the increasing number of herbicide-resistant weeds and loss of biodiversity (Box 1). Also, weed science has been exposed to the critique that management practitioners, weed biologists and ecologists studying plant populations work largely in isolation and that the failure to adopt an interdisciplinary approach has left more fundamental aspects of weed biology unaddressed. (Ward, Cousens, Bagavathiannan, Barney, Beckie et al. 2014; Wyse 1992). From a scientific point of view, and with the exception of recent advances in agroecology (Hatcher & Froud-Williams 2017; Jordan et al. 2016; and references therein), there have been so far only modest efforts to address new issues such as global warming, invasive alien species and client diversification (forestry, landscape management, urban, amenity and industrial area maintenance, transportation; Follak & Essl 2013), or to use agricultural weeds as model study systems to articulate and test novel hypotheses that help advancing both weed management as well as ecological and evolutionary theory (Ward et al. 2014). The inability to shift focus has contributed to the steady decline of active weed scientists seen in most European countries over the past few decades (Fernandez-Quintanilla et al. 2008). The increasing problem with the evolution of herbicide-resistant weeds reveals the immediate need for developing diversified weed management practices that reduce the reliance on herbicides (Lamichhane, Dachbrodt-Saydeeh, Kudsk & Messean, 2016). This has generated a renewed interest in weed management with a focus on integrated approaches and on sustainable and long-term considerations (Hall, Van Eerd, Miller, Owen, Prather et al. 2000; Young, Pitla, Van Evert, Schueller & Pierce 2017, cf also www.iwmpraise.eu). In summary, weed science, the more applied discipline and the one that institutionally is “in charge” of weed management in practice, has mainly focused on herbicide-based weed management in Europe. While there is a (long) history of European ecologically-based weed scientists, their influence on weed management has remained rather marginal (Fernandez-Quintanilla, et a. 2008).

The younger field of invasion science, in contrast, has become a very active and highly productive sub-discipline of ecology (Kueffer, Pyšek & Richardson 2013;

Richardson & Ricciardi 2013) and more recently also of evolutionary biology (Colautti & Lau 2015). This is indicated by its extensive coverage in many highly cited journals and dedicated sessions in leading conferences in ecology, conservation biology, biogeography and evolution. Scientifically, biological invasions offer a unique opportunity to study species interactions when conquering a new environment, often by multiple introductions and replicated on different continents, which has yielded insights into key concepts in biology (Callaway & Maron 2006; Jeschke, Gómez Aparicio, Haider, Heger, Lortie et al. 2012; Richardson et al. 2013; Box 1). Invasion science, with its dichotomous view of species based on origin (native vs. exotic status as a predictor of context-dependent plant performance), is presently plateauing off. It is partially merged back into experimental ecology and partially subsumed into a new paradigm in the field of ecology, that is ecological novelty dealing with community and global change ecology including the redistribution of species throughout the world (Hobbs, Arico, Aronson, Baron, Bridgewater et al. 2006; Kueffer 2015). The key societal interest in biological invasions remains the predicted increase in impact on biodiversity, ecosystem services and human well-being, causing huge socio-economic costs, and the imperatives to prevent and manage these impacts. This is reflected by many new European research programs on invasive alien species and in the newly established regulations on invasive alien species by the European Commission DG Environment (http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R1143&from=FR). However, in contrast to the well-established national and regional institutional settings to manage agricultural weeds and pests, there is still a need for developing and implementing multi-stakeholder approaches to manage invasive alien species on the ground, including systems for early detection of new invaders and rapid response, and for long-term and sustainable management measures for widely established invaders.

In this article, we argue that in Europe, cross-fertilization of the “old” and experienced weed science with the “young” invasion science bears a great potential to advance sustainable management of noxious plants. We illustrate this by outlining and discussing key components of a recently accomplished international, interdisciplinary network (EU-COST Action SMARTER; FA1203; http://www.cost.eu/COST_Actions/fa/FA1203?parties) that aimed to develop efficient and sustainable measures against common ragweed (*Ambrosia artemisiifolia*) in Europe.

Crop weeds vs. invasive alien plants

Traditionally, the focus of weed science has been on agricultural practices with weeds being plants that constitute an important threat to crops (Fernandez-Quintanilla et al. 2008; Hall et al. 2000; Jordan et al. 2016). Invasion science deals with the causes and consequences of organisms introduced into areas outside their native range, and in the case of plants, mostly on species that conquer semi-natural and natural ecosystems (Kueffer et al. 2013). In this paper, we will focus on Europe and use the term “weeds” for plants native to Europe and mainly harmful to agricultural and horticultural crops, while we use “invasive alien plants” (IAP) for species non-native to Europe and mainly imposing risks to natural or semi-natural habitats. We understand that native weeds can also impose threats to conservation areas (e.g. *Rubus* spp.), while several of the IAP can also be crop weeds (cf. e.g.

Follak, Schleicher, Schwarz & Essl 2017; Fried, Chauvel, Reynaud & Sache 2017; Holzner & Glauninger 2005).

In Europe, weed science and plant invasion science have developed as two distinct research areas, with different researchers from different institutions, attending different symposia and publishing in different journals. To assess whether this division can at least partly be explained by different target species and habitats, we analyzed various noxious species lists by adding occurrence in crop and/or non-crop habitats (crop vs. environmental weeds) and origin (native vs. alien to Europe) for each species (Fig. 1). Indeed, only 26% of the 281 important crop weeds in Europe (Weber & Gut 2005) are non-native to Europe (Fig. 1A). Only about one-eighth of them are restricted to arable fields, and more than half of them spread also to semi-natural habitat types (like *Amaranthus* spp., *Ambrosia* spp., *Erigeron* spp.). In lists of IAP, less than 10% of the species are restricted to crop fields (Kumschick, Bacher, Evans, Markova, Pergl et al. 2015; Lambdon, Pyšek, Basnou, Hejda, Arianoutsou et al. 2008; Figs 1B, C). Van Kleunen, Dawson, Essl, Pergl, Winter et al. (2015) listed 100 ornamental plants with high potential to escape to disturbed semi-natural environments and become an environmental weed. Fifty-one of these were non-European, and only half of all can also invade crop fields, but none are restricted to crop fields (Fig. 1D). Finally, at the worldwide scale, almost none of the land plants listed as top-100 IAP by the IUCN (Lowe, Browne, Boudjelas & De Poorter 2000) have been mentioned as agricultural weeds.

Nevertheless, the two research fields are coming increasingly closer together. A simple search in the Web of Science for the term “invasive plant” in the journal “Weed Research” showed a steady increase in the relative number of publications over the past three decades, and a similar increase for publications with the term “weed” in “Biological Invasions” over the past two decades ($r^2 = 0.77$, $p < 0.0001$ and $r^2 = 0.55$, $p = 0.0007$, respectively).

We acknowledge that the situation is quite different in the New World (Americas, Australia, New Zealand), where many of the crop and grassland weeds, as well as weeds of disturbed early successional habitats are of ’Old-World’ origin, i.e. alien, and given the extensive nature of parts of their agriculture, alien invasive weed management became part of weed science. In the New World, environmental weed management started with the enforcement of environmental legislation only in the 1980s, but still much earlier than in Europe, where the accumulated impact of invasive alien species has been realized only since early 2000 (Hulme, Pyšek, Nentwig & Vilà 2009). For this reason, weed and invasive plant management developed much more as a joint venture in the New World, and ecologically-based management, although still marginally applied, has been developed earlier (cf. e.g. Cousens & Mortimer 1995; Inderjit 2010; Liebman, Mohler & Staver 2004; Radosevich, Holt & Ghersa 1997). Nevertheless, we propose that our integrative approach is widely applicable, which is supported by previous calls for greater integration of weed science with other areas of biological research (Davis, Hall, Jasieniuk, Locke, Luschei et al. 2009; Hatcher & Froud-Williams; 2017) and successfully integrated approaches on handling invasive pests (e.g. Isard, Barnes, Hambleton, Ariatti, Russo et al. 2011).

Common ragweed, an ideal ‘bridge species’

Here, we outline how we - in the framework of an interdisciplinary and international research program - deliberately created synergies between weed science and invasion science to develop sustainable management schemes against common ragweed (ragweed in the following). Ragweed is one of the economically most important plant invaders in Europe, this is the result of it having severe impacts on human health and because it is also a crop weed. Moreover, it is increasingly affecting biodiversity and nature conservation (Essl, Biró, Brandes, Broennimann, Bullock et al. 2015; Pál 2004). The species grows in a wide range of habitat types including crop fields, ruderal areas and grasslands and along rivers, roads and railways, thus representing both early-successional as well as late-successional habitats with open soil (such as dry grasslands, open sand and gravel banks, open forests; cf. Essl et al. 2015 and references therein). Each plant can produce millions of wind-dispersed pollen grains that elevate concentrations of pollen in the air near to the source or remotely through transport in the air (de Weger, Pashley, Šikoparija, Skjøth, Kasprzyk et al. 2016; Sommer, Smith, Sikoparija, Kasprzyk, Myszkowska et al. 2015). Clinically relevant sensitization rates among the allergic population are found throughout Europe and they are highest in countries where the plant is widely distributed and abundant (e.g. Hungary; Heinzerling, Burbach, Edenharter, Bachert, Bindslev-Jensen et al. 2009). Ragweed is predicted to further spread northeast in Europe (Essl et al. 2015; Sun, Brönnimann, Roderick, Poltavsky, Lommen et al. 2017), and airborne ragweed pollen concentrations are forecast to increase about 4 times by 2050), with one third of the airborne pollen increase being due to on-going seed dispersal, irrespective of climate change. The remaining two-thirds are related to climate and land-use changes that will extend ragweed habitat suitability in northern and eastern Europe (Hamaoui-Laguel, Vautard, Liu, Solmon et al. 2015).

While herbicide treatments and mechanical control have been developed and implemented as short-term weed control measures in Europe, particularly in agricultural settings (Buttenschøn, Waldispühl & Bohren 2008), these methods do not provide sufficient control in the long term, as proven by the evolution of herbicide-resistant populations (Délye, Meyer, Causse, Pernin & Chauvel 2015; Essl et al. 2015). Moreover, their use is often not tailored to specifically control common ragweed (e.g. mowing regimes along roadsides mainly serve traffic safety, and herbicide applications in crop fields usually target the entire weed community), not cost-effective for all habitat types, and/or limited to some habitat types due to their associated environmental impact. Potential long-term control methods that remain to be implemented in Europe are the establishment of a competitive vegetation (Yannelli, Karrer, Hall, Kollmann & Heger 2018) and classical biological control, i.e. the release of specialist natural enemies originating from the native range (Gerber, Schaffner, Gassmann, Hinz, Seier et al. 2011).

Ragweed thus constitutes an ideal “bridge species” between weed and invasion science by linking the management strategies and tools of the two sectors. For assessing its overall impact and management success, and to develop an integrated management approach, weed scientists and invasion biologists, but also experts from other disciplines (public health, aerobiology, economics, etc.) have to combine their efforts by forming a network for collaborations. It further requires the involvement of a large spectrum of both public and private actors, ranging from farmers to road and railway services, environmental advisory services, municipalities, up to national and European authorities and organizations in health and agriculture.

We tackled this challenge in the framework of EU COST Action FA 1203 on the “Sustainable Management of *Ambrosia artemisiifolia* in Europe” (in the following "SMARTER"). We initiated and developed a multi-, inter- and trans-disciplinary approach by interconnecting experts in weed management, plant distribution monitoring, plant invasion biology, aerobiology, public health and economics and establishing continuous exchange with stakeholders involved in *Ambrosia* management. Box 1 summarizes the objectives and the structure of SMARTER. In the following section, we outline six topics illustrating our approach to ragweed management. In the final section, we briefly summarize our achievements, discuss limitations and give examples of continuative interdisciplinary studies. We argue that the SMARTER approach can also be applied to the management of other noxious plants.

Enabling synergies by inter-linking weed science with plant invasion science, and by inter- and trans-disciplinary cooperation

Population dynamics for the design and evaluation of management

Modelling the demography of populations is increasingly demanded to guide policy and management of biological invasions (Caplat, Coutts & Buckley 2012). For instance, by projecting effects of experimentally tested management interventions, population models can compare the longer-term population-level effects of management interventions, and can reveal what timing, frequency and duration of these interventions are most cost-effective in bringing down population sizes (e.g. Zhang & Shea 2011). This requires an understanding of the variation in the dynamics of invasive populations in space and time, especially in variable environments (McDonald, Stott, Townley & Hodgson 2016), since analyses of individual populations or years could misguide management (e.g. Evans, Davis, Raghu, Ragavendran, Landis et al. 2012). Due to the international composition of SMARTER, we were able to quantify the spatio-temporal variation in local demographic processes of ragweed using over 50 naturalized and unmanaged populations of ragweed across the European continent, covering different climates and habitat types in 17 countries (please see comments on Appendix A: Fig. 1A). The data are presently being used to construct climate- and habitat-dependent demographic models allowing the comparison of management effects across many environments. The first results indicate temporal variations in demographic processes, and identify the most important environmental drivers of spatial variation in reproductive output (i.e. weather and habitat types) (Lommen, Hallmann, Jongejans, Chauvel, Leitsch-Vitalos et al. 2017). Our site-specific population models of ragweed already revealed that the ragweed leaf beetle *Ophraella communa* LeSage (see comments in Appendix A: Fig.1B) can significantly reduce the projected population growth rates of ragweed in some years and places below the population replacement level (S.T.E. Lommen, unpublished results). We also compared the cost-efficiency of different mowing regimes for ragweed populations along roadsides and in grasslands, and found that the optimal regime was consistently the same for populations in different geographical locations and in different years (Lommen et al., 2018; cf. below). Such a population dynamics approach may also be useful for projections of effects of weed management on ragweed in crop fields by including these in existing weed population models (e.g. Heard, Rothery, Perry & Firbank 2005; Shea 2004).

Biological control management

Classical biological control of weeds constitutes the importation and release of specialist natural enemies from the weed's native range to reduce its abundance in the introduced range (Müller-Schärer & Schaffner 2008). Until recently, biological control of weeds has mainly focused on IAP species invading semi-natural and natural habitats (Müller-Schärer & Schaffner 2008). The emerging successes in classical biological control of the annual weeds *Parthenium hysterophorus* (L.) in Australia and *A. artemisiifolia* in both Australia and China, however, underline that this control method can also be applied to annual IAP species that also cause problems in crop fields (Sheppard, Shaw & Sforza 2006). Moreover, new biological control solutions on the basis of inundative biological control using plant pathogens naturally present in the environment or natural compounds with herbicidal activities deserve to be reconsidered (Masi, Zonno, Cimmino, Reveglia, Berestetskiy et al. 2017). While the bioherbicide approach was originally more anchored in weed science, the study of invasive plant-resident pathogen interactions has raised a lot of interest in invasion ecology. In North America, some of these native fungal and bacterial pathogens are currently tested for their suitability as bio-herbicides against invasive species (e.g. Meyer, Beckstead & Pearce 2016).

SMARTER conducted host-specificity and impact studies with a set of candidates for the classical (arthropods from the native range) and inundative biological control (native bacteria, fungal pathogens and their metabolites) of ragweed for Europe. Specifically, SMARTER responded quickly to the accidental introduction of the ragweed leaf beetle *O. communa* in Europe (Müller-Schärer, Lommen, Rossinelli, Bonini, Boriani et al. 2014), which is successfully used as a biological control agent of ragweed in China (Sun et al. 2017; Sun, Zhou, Wang & Müller-Schärer 2018). Our interdisciplinary team managed to assess both the potential benefits and risks of this species (see Appendix A: Fig. 1B) (Bonini, Šikoparija, Prentović, Cislaghi, Colombo et al. 2015; Lommen, Jolidon, Sun, Eduardo & Müller-Schärer 2017; Mouttet, Augustinus, Bonini, Chauvel, Desneux et al. 2018; Sun et al. 2017). Host specificity studies carried out both under laboratory and open-field conditions so far indicate that *O. communa* poses little risk to commercially grown sunflower and to native endangered plant species (Müller-Schärer, Schaffner et al. 2016). Because it might generate high economic benefits by reducing health costs in the regions heavily invaded by common ragweed (cf. Mouttet et al. 2018), we propose that European and national competent authorities should follow the example of France and conduct pest risk assessments (ANSES 2015) that facilitate the decision process on how to respond to the arrival of this biological control agent in Europe. Since the use of classical biological control for the management of noxious plants is still in its infancy in Europe, SMARTER also organized workshops to promote the integration and harmonization of national and European-wide regulations dealing with biological control (Shaw, Schaffner & Marchante 2016), together with the European and Mediterranean Plant Protection Organization (EPPO), the International Organization for Biological Control (IOBC) and other international and European stakeholders (e.g. http://archives.eppo.int/MEETINGS/2015_conferences/biocontrol.htm).

Spatial modelling

Changes in climate, land use and trade are expected to favor the spread of ragweed in Europe (Essl et al. 2015; Sun et al. 2017). Our recent species distribution models predict that ragweed in Europe will rapidly spread towards the northeast, while its biocontrol candidates would not keep pace with this spread. This identifies the need

to develop climatically adapted strains for biological control in regions where ragweed is currently unlikely to be controlled (Sun et al. 2017).
The availability of the required plant occurrence records of invasive species is often limited. For an anemophilous species like ragweed, spatial data on airborne pollen concentrations can help to construct occurrence maps. SMARTER members constructed gridded pollen source inventories using top-down methods by integrating land use data and local knowledge of plant ecology into spatial distribution models of airborne pollen (Skjøth, Smith, Šikoparija, Stach, Myszkowska et al. 2010). We showed that these inventories reflect variations in plant abundance and effectively link land management to atmospheric concentrations of ragweed pollen (e.g. Karrer, Skjøth, Šikoparija, Smith, Berger et al. 2015) and that it is also possible to integrate the effect of *O. communa* after its appearance in Northern Italy (Bonini, Šikoparija, Skjøth, Cislaghi, Colombo et al. 2018). By integrating airborne pollen concentrations with numerical atmospheric transport models, we also provide an early warning system for risks of exposure to airborne ragweed pollen in presently uninvaded countries (Sommer et al. 2015). In a further study, we are presently comparing two approaches for assessing ragweed infestations and for producing reliable background data for its management by (i) mapping ragweed presence in Europe using a top-down approach (where infested ragweed habitats are based on a combination of expert knowledge, land cover data and calculated pollen integrals) and (ii) a bottom-up approach (using geographically referenced ragweed occurrences and abundances where available). The two approaches provide comparable results, which allows for the reliable prediction of high ragweed densities using the top-down approach in cases where ragweed occurrence data are not available (Skjøth, Sun, Gerhard, Branko, Matt et al. 2018).

Overcoming conflicting management objectives and reconciling management activities of the various stakeholders

Current habitat management and agricultural practices are not aimed at reducing ragweed specifically, and can even foster its spread. Not cleaning farm machinery after cultivation of ragweed-infested areas, and an inappropriate frequency and timing of mowing of linear corridors along road shoulders and water body embankments can accelerate the spread of ragweed (Karrer, Milakovic, Kropf, Hackl, Essl et al. 2011). To reduce the population size of ragweed (i.e. limit seed production) and also avoid pollen production, management needs to be tailored to meet both aims when managing this protandrous monoecious plant. One single cut before peak male flowering may reduce the airborne pollen load without affecting ragweed seed output and population size, while two cuts later in summer reduce population size without affecting pollen loads. Only the costly combination of all three cuts meets both aims (see Appendix A: Fig. 1C; Milakovic, Fiedler & Karrer 2014), so the adoption of new methods or combinations (e.g. with biological control) is needed to achieve cost-effective control. In a recent study of roadside populations in Austria, we integrated the effects of four experimental mowing regimes on plant performance traits of five years and experimental data on seed viability after cutting to further determine the cost-effectiveness of mowing regimes varying in frequency and timing. The prevailing 2-cut regime in Austria (cutting during vegetative growth in June and just before seed ripening in September) performed least well. By applying our previously established plant population model, we further explored effects of five theoretical mowing regimes to identify the most cost-effective schemes for each cutting frequency (1–3 cuts). They all included the cut just before female flowering, highlighting the importance of cutting at this moment (here in August) and showing the usefulness of population models in designing cost-effective mowing regimes that will lead to both pollen and seed reductions (Lommen et al. 2018). The same approach could be applied to reconcile conflicting management requirements for ragweed in crops, i.e. between early-season control to avoid yield losses vs. late-season control to avoid pollen and seed production to minimize health effects.

Furthermore, a lack of coordination of management aims and strategies can create conflicts between managers of the different habitats invaded by ragweed. Management imperatives may be opposite (e.g. for roadsides, biodiversity conservation for natural areas) and available practices differ (roadside mowing, herbicides for cultivated areas) (see Appendix A: Fig. 1D). Seed flows between habitats remain poorly understood and this can introduce doubts about the need for control by a manager if the neighboring environment appears to be poorly managed. For example, an additional investment of a roadside manager can encourage neighboring farmers to improve the management of their field during the intercropping period and thus promote a joint effort against ragweed. SMARTER organized both regional and European-wide stakeholder meetings to reconcile management activities of the various stakeholders by sharing biological, ecological and agronomical data between stakeholders (e.g. Bonini, Gentili & Müller-Schärer 2017). Proof of success is needed to jointly work towards a long-term goal. An overview of where to apply which management tool and combination by taking a region-specific and successional view of habitat occupancy is presently in preparation (Kudsk et al., in preparation).

Economic impact assessment of ragweed and management evaluation

Stakeholders involved in ragweed management constitute multiple sectoral (e.g. biophysical, technological, economic) and institutional dimensions (private, public) and are linked to interventions across different spatial levels (e.g. farm, village, national, continental level). Evaluating the management of ragweed, therefore, requires an interdisciplinary approach, assessing effects on ragweed distribution and spread, crop yields, airborne pollen, ragweed-related medical parameters and the costs of these (see Appendix A: Fig. 1E). SMARTER collected and merged datasets in order to map the distribution (Sun et al. 2017) and related impact of ragweed in Europe. These include observational and modelled data that can be used for making *ex-ante* assessments of economic and health impacts under different management options using the impact pathway approach that has been applied to air quality for decades (e.g. Cifuentes & Lave 1993; Richter, Berger, Dullinger, Essl, Leitner et al. 2013) The output of this Action helps decision makers in selecting region-specific and cost-effective measures for controlling the spread and mitigating the impacts of ragweed. In a joint project between economists, aerobiologists, public health experts and ecologists, we recently assessed the potential economic benefits of an establishment of *O. communa* in the heavily invaded Rhône-Alpes region in south-eastern France. We estimated that the number of days with a ragweed pollen risk at which sensitive people express symptoms would be reduced by 50% and the medical costs due to common ragweed would subsequently decrease by 5-7 M € annually (Mouttet at al. 2018).

Knowledge and technology transfer: involving stakeholders and forming future experts

To transform scientific understanding into practice, it is important to co-design and co-implement management strategies in collaboration with the various stakeholder groups affected by noxious weeds (See comments above) (Clark, van Kerkhoff, Lebel & Gallopin 2016; Oude Lansink, Schut, Kamanda & Klerkx 2018). Invasion science can learn from agricultural science, where knowledge transfer among stakeholders has led to the development of practical and profitable innovations (Elueze 2016). On the other hand, weed management could benefit from invasion science by taking a more spatial and holistic approach to coordinate and integrate management across habitats and the respective stakeholders responsible for management (e.g. Grice, Clarkson & Calvert 2011; Shackleton, Le Maitre, van Wilgen & Richardson 2017; see Appendix A: Fig. 1D). In order to conduct research on ragweed management that is practically relevant, we included academic and non-academic stakeholders in the research design and programs (Karrer et al. 2011) as well as in the dissemination of the results (Gentili, Bonini & Müller-Schärer 2017). One strategy to identify and manage common ragweed that has proven particularly successful was implemented in Switzerland by sub-national working groups and later on coordinated by weed scientists from the Swiss Agricultural Research Institute Agroscope. Building on public information campaigns and agricultural advisory services, ragweed infestations were mapped across Switzerland, treated and subsequently subjected to a monitoring programme because of the invasive character of ragweed (Bohren, Mermillod & Delabays 2006). Such an approach based on agricultural institutional settings is likely to be suitable also in other parts of Europe with currently low levels of ragweed invasion, particularly countries in Northern Europe.

Also, SMARTER contributed to form a new generation of invasion and weed scientists through multidisciplinary training schools and exchange visits for early stage researchers (which have resulted in new collaborations and papers, e.g. Yannelli, et al. 2018), which is a focus of COST (http://www.cost.eu). We provided them with knowledge of a wide range of cutting-edge technologies for understanding the causes, monitoring the spread, and predicting future scenarios of the invasion (e.g. the use of drones for weed mapping and detection, smart technologies for precise and environmentally friendly herbicide application, genetics and population dynamics studies) and for transforming novel scientific understanding into practical application (see Appendix A: Fig. 1A). As an example of stakeholder involvement, we brought together early-stage plant scientists and road maintenance workers to discuss vegetation management (cf. references above).

Furthermore, SMARTER developed a conceptual framework for designing invasive weed management strategies (Oude Lansink et al. 2018). The framework supports the systematic identification, categorization and analysis of the needs and interests of different stakeholders across local, national and supra-national levels, and links this to incentives for engaging in individual and/ or collective invasive weed control.

SMARTER - a template for a more efficient and sustainable management of invasive plants and weeds: achievements, limitations and the way forward

Our "SMARTER" consortium initially consisted of researchers already actively working in the field of weed /IAS science and management, most of them already working with common ragweed. This is in line with the objective of EU-COST that does not finance research, but mainly supports networking activities. By doing this and in a first step towards an interdisciplinary project, we brought together researchers from different disciplines, countries and both scientific and non-scientific parties (stakeholders, regulators) to achieve a well-established multidisciplinary team. This already resulted in a good number of publications in the various disciplines. Capitalizing on the established network, we then initiated a number of truly interdisciplinary studies that have already well advanced, such as quantifying the effects of common ragweed on public health across Europe and the potential impact of the ragweed leaf beetle on the number of patients and healthcare costs in Europe, which is both relevant to advance science and to its application.

The established SMARTER network is presently extended by including population genetics, experimental evolution and genomics tools to potentially increase the effectiveness of management interventions and predicting their long-term effect. Previous studies and those carried out by the SMARTER Task Force on Genetics revealed that introduced *A. artemisiifolia* populations in Europe (and Asia) are probably a mixture of different native populations (Genton, Shykoff & Giraud 2005; Chun et al. 2010; Li et al. 2012; Causse et al. 2014), with observed genetic variation mostly occurring within rather than between populations. This high genetic variation within populations might allow for selection and adaptation and thus mitigating management interventions, such as in response to cutting regimes and biological control. In this context and by collaborating with population geneticists and evolutionary biologists, we now work on improving predictions for future long-term benefits and risks of the potential biological control by the ragweed leaf beetle *O. communa.* For this, we initiated a novel experimental evolutionary approach to assess the beetle's potential to select for resistant/tolerant ragweed populations, as well as the beetle's potential for evolutionary adaptation to novel biotic (host plants) and abiotic (colder temperature for spreading into the yet unsuitable habitats in Central Europe) conditions, using selection experiments, next generation sequencing and bioassay approaches. We now also extend the biological control part to further agents, including the mite *Aceria artemisiifoliae* sp.nov. (Vidović, Cvrković, Rančić, Marinković, Cristofaro et al. 2016) and the tortricid moth *Epiblema strenuana* Walker (Yaacoby & Seplyarsky 2011), both also recently and accidentally introduced to Europe.

A further item, which has yet to be achieved, is the elaboration of habitat- and region-specific management interventions by combining the various methods presently elaborated, such as establishing competitive vegetation, cutting regimes and biological control measures. An experimental approach combining an establishment of a competitive vegetation and *O. communa* herbivory has recently been carried out in Northern Italy (Cardarelli, Musacchio, Montagnani, Bogliani, Citterio et al. 2018). A further study addressed joint effects between natural occurrences of some polyphagous insects and pathogens in Hungary (Kazinczi & Novák, 2014).

Ragweed is just one example from a large number of invasive plants that requires integration across different disciplines. The well-established network can now similarly be used to tackle other Old World (Afro-Eurasian) target species. (see Appendix A: Table 1). *Parthenium hysterophorus*, for instance, a close relative of ragweed and one of the worst invasive plant species worldwide, also affects different actors, including those representing human health, agriculture and environment. Other species may require cooperation among other actors and research disciplines, e.g. environment with engineering (*Reynoutria* spp.) or agriculture with environment and trade (*Eichhornia crassipes* (Mart.) Solms) (see Appendix A: Table 1). Typical IAP species are increasingly being reported from crops (e.g. *Ageratum conyzoides* L., *Abutilon theophrasti* Medic., *Erigeron canadensis* L.; cf. also Follak, Schleicher, Schwarz & Essl 2017; Holzner & Glauninger 2005), and native crop weeds are invading early-successional (e.g. ruderal habitats such as along railway tracks, roads and industrial areas) as well as late-successional habitats with open soil, such as dry grassland and open forests (e.g. *Cirsium arvense* (L.) Scop., *Echinochloa crus-galli* (L.) P.Beauv., *Chenopodium album* L., *Convolvulus arvensis* L, *Cyperus esculentus L.*) (Table 2). Invasive plant species and weeds usually have strong socio-economic impacts, particularly in developing countries, expanding the list of actors in Table 2. Implementation of management strategies should therefore always consider the regional and local societal and economic environment. Projects that implement sustainable management of invasive plant species can benefit from existing structures and management practices, such as agricultural extension services, thereby profiting from a system with foundation in weed (and pest) science. Invasive species do not stop at habitat or political boundaries, calling for a trans-national and trans-sectoral coordination of management activities.

Similarly, the management of traditional crop weeds may greatly benefit from collaboration with non-agricultural actors and domains by streamlining specific aims as outlined above for ragweed (see Appendix A: Fig. 1D). The adoption of integrated weed management rather than herbicide-based weed control will shift the focus from short-term benefits of weed management to medium- and long-term benefits (Young et al. 2017).

In summary, forming an interdisciplinary team from experts working in isolation via multi-disciplinary groups took us seven years. This process had been initiated by a few motivated researchers, with little money, and irrespective of institutional and other systemic barriers. We managed to involve stakeholders along the way, but clearly a better approach would have been to involve them from the beginning.

The increasing number of herbicide-resistant weeds and their resistance to a rising number of active ingredients, together with an increasing number of banned herbicides might support a process of forming interdisciplinary consortia. This also applies to the increasing number of IAP species and the lack of an efficient and sustainable management. Major hurdles remain, including the absence of a strong interest for building up such networks both from the private (agrochemical industry) and the public sector (researchers, phytosanitary services, national and European authorities), as well as for a harmonization of management intervention (including prevention and biological control measures) against IAP species across Europe.

The SMARTER approach is based on a close cooperation among weed science, invasion science as well as other research disciplines and actors and domains affected by ragweed invasion and management across Europe. We propose that it can serve as a template for establishing trans-national, trans-sectoral and interdisciplinary consortia, which can undertake comprehensive impact analysis, efficient management and evaluate subsequent success. A better involvement of stakeholders from the very beginning as laid out in the ‘multi-actor approach’ now promoted by the EU (being now compulsory for all Horizon 2020 calls within the agricultural area) would greatly benefit and further advance our SMARTER approach. Such an approach can then be used for numerous other weeds and invasive alien species that impact on multiple actors and domains, habitat types and regions. Furthermore, such research cooperation also offers opportunities to train early-stage researchers in interdisciplinary research, a key skill for future collaborative research projects for the sustainable management of noxious plants.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at XXXXX.

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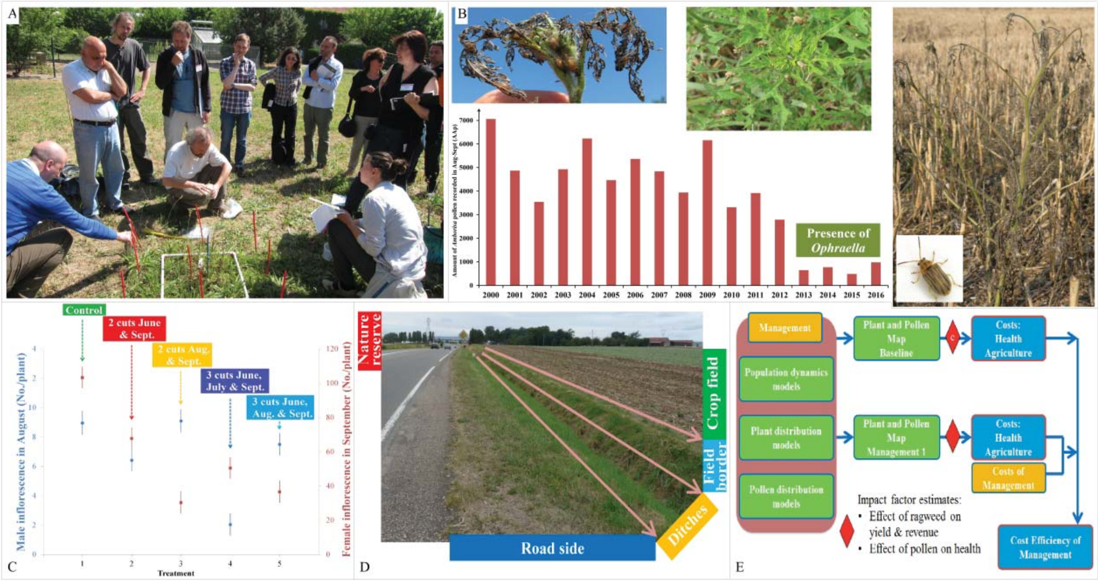
Appendix A: Fig. 1. Achievements from inter-linking “Weed Science” with “Plant invasion science”, and from interdisciplinary and/or international cooperation



(A) We monitored 50 natural populations of *Ambrosia artemisiifolia* across Europe in 2014-2016, covering different climatic and habitat conditions, to assess environmental drivers underlying spatial variation in its demographic performance. The resulting demographic models allow the identification of optimal habitat- and region-specific management interventions. This is our workshop on demographic research. Capacity-building in the field of understanding, monitoring and managing noxious plants constitutes a sustainable output of our SMARTER approach.

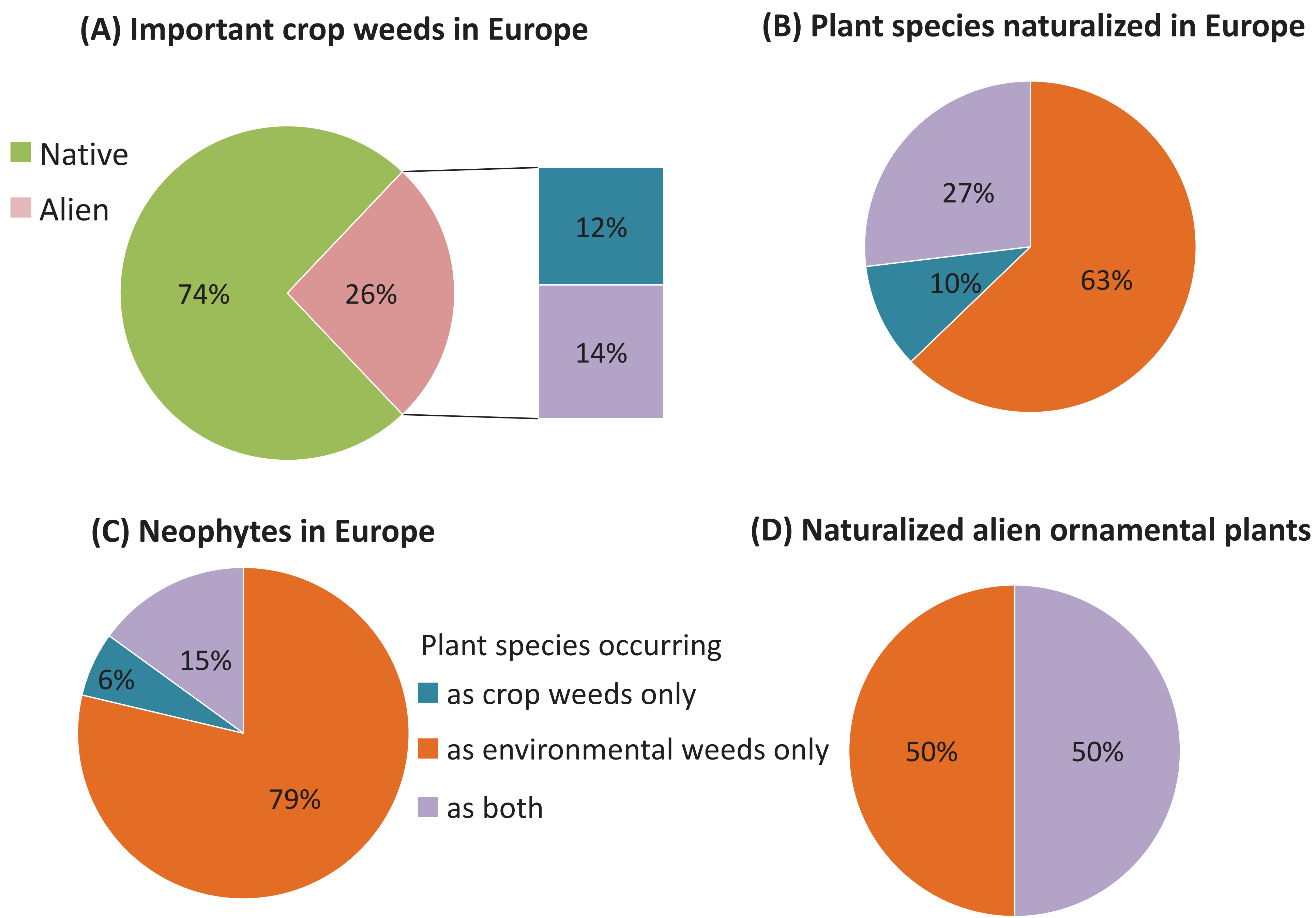
(B) We quantified the impact of the accidentally introduced ragweed leaf beetle *Ophraella communa*, first recorded in Europe in 2013, on pollen and seed production of ragweed*.* Aerial pollen concentrations dropped by 80% in the area of Milan, with regional savings in health costs of millions of Euros per year (graph adapted from Bonini et al. 2015).

(C) We developed management options that overcome conflicting management objectives. The traditional two cutting interventions reduce either pollen or seed output of the monoecious ragweed Thus, managing ragweed as a crop weed with minimum cuts might help the farmer, but could extend health problems. Three cutting interventions are needed to significantly reduce both pollen and seeds. Combining cutting with biological control is needed to achieve cost-effective control (graph redrawn from Milakovic et al 2014).

(D) We discovered that reconciling management activities of the various stakeholders is needed to achieve efficient management at the regional scale. Here, five different stakeholders are concerned. Investments by one (e.g. road service) might greatly benefit another stakeholder (e.g. farmer), and failing management by one affects all. Monitoring of the weed dynamics therefore needs to be extended from the local to a larger spatial scale.

(E) Our economic framework for the evaluation of the management of *Ambrosia*. The ‘management module' produces maps of the distribution of *Ambrosia* plants and pollen in a baseline scenario, including a basic set of current management practices. The economic evaluation of the baseline and alternative management scenarios computes the costs for agriculture, health and management (e.g. FADN 2015; Soliman et al. 2010). Cost-efficient management scenarios are those where impact savings outweigh the costs of the management practices.

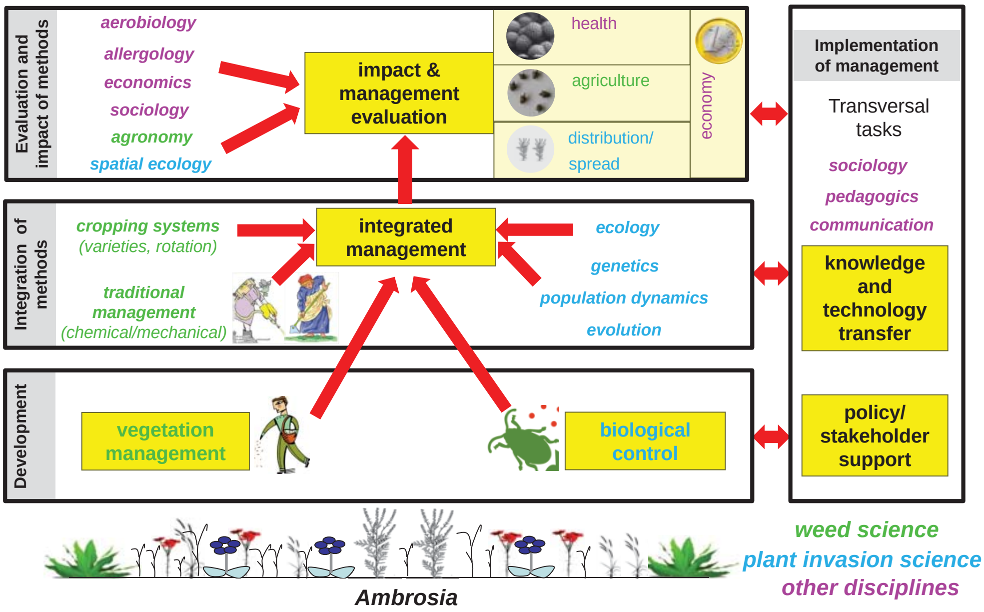
Fig. 1. Analysis of various European noxious species lists for species occurrences in crop and/or non-crop habitats (crop vs. environmental weeds) and origin (native vs. alien to Europe). (A) Important crop weeds in Europe (N=281) (Weber & Gut 2005), (B) Plant species naturalized in Europe (N=145) (Lambdon et al. 2008), (C) Neophytes in Europe (N=127) Kumschick et al. 2015), (D) Naturalized alien ornamental plants (N=100; 51 are non-European) (van Kleunen et al. 2015).


(A) Important crop weeds in Europe
Native
Alien
74%
26%
12%
14%
(B) Plant species naturalized in Europe
27%
10%
63%
(C) Neophytes in Europe
15%
6%
79%
Plant species occurring
as crop weeds only
as environmental weeds only
as both
(D) Naturalized alien ornamental plants
50%
50%

Box 1. Differences in the setting, focus and strengths between "Weed Science" and "Plant Invasion Science" as practiced in Europe

Weed Science	Plant Invasion Science
Setting	
long tradition supported by agronomy	new fields supported by ecology & evolution
mainly driven by practical management/ control questions and innovations in agricultural engineering	mainly driven by fundamental scientific questions and ecological theories (also by practice of conservation)
many target species (weeds), but only one focal plant (crop)	one target species (invasive alien plant), but many focal species (plant community)
predominantly native species (see Fig. 1A)	exclusively non-native species
single stakeholder (agriculture)	many stakeholders (conservation, public health, agriculture, forestry)
policy: EU Regulation concerning management practices (herbicide use, intercrop covers), but few regulations on species except for parasitic weeds	EU Regulation 1143/2014 on Invasive Alien Species, EU regulations on the introduction of exotic biological control agents in progress
Focus	
focus on cultivated land, close landscape structure	on community/ ecosystem/ biogeography
main focus for management: reduction of biomass at a site	reduction of abundance and spread, mitigation of impact
spatial scale: local to regional; the field	local, regional to global; natural or man-made habitats
mainly studied at national research institutions	universities and environmental research institutions
possibility to manage the habitat using perturbation: abundant (soil tillage, crop rotation, herbicide, crop competition)	limited, especially in natural habitats
experimental evidence and ecological/evolutionary theories: on plant competition and crop breeding (for shading and herbicide-resistance)	on biotic (community) resistance, phylogenetic relatedness and community assembly, rapid evolution, local adaptation
Strong points	
application-driven, providing practical advice to practitioners	strongly rooted in basic ecology, drawing insights from many disciplines and using new technologies to identify drivers
providing efficient control of weeds	getting great interest from society and research community
good links to the private sector	good links to basic science
good knowledge of the species' biology (morphology, taxonomy, life cycle, distribution)	good knowledge of the species' ecology and evolution (species interactions, population dynamics, genetics, spatial processes)

Box 2. The structure of the COST Action SMARTER: capitalizing on weed science and plant invasion science to develop and implement sustainable management of *Ambrosia artemisiifolia* across habitat types and regions.



We started the trans-sectoral and international EU COST Action SMARTER "Sustainable management of *Ambrosia artemisiifolia* in Europe, FA1203, www.ragweed.eu) in 2013. Although chemical and mechanical control methods have been partially implemented against ragweed in Europe, control efforts and methods vary greatly between geographical areas. More sustainable control strategies such as biological control or vegetation management, while successfully implemented in other continents (China, Australia), were lacking in Europe (Gerber et al. 2010). The development of such innovative strategies was needed, as large areas of ragweed infestations are on non-arable land, such as ruderal areas or along linear transport infrastructures (rivers, roads or railway tracks) where traditional methods are either too expensive or prohibited.

During four years, we brought together over 250 professionals - researchers and various stakeholders - from over 30 countries, mostly European, but also including Armenia, Canada, China, Georgia, Iran, Japan and Russia.

SMARTER elaborated six tasks (yellow blocks) through the international collaboration of multiple disciplines. Building on expertise from weed science (in green) and plant invasion science (in blue), we developed new control methods (lower panel) and assessed the integration of control methods (middle panel). For the evaluation of management impact (upper panel, with subtasks in light yellow), expertise from other disciplines (in purple) was crucial, too.

Towards a successful implementation of management strategies (vertical panel) SMARTER trained young scientists in the field of understanding, monitoring and managing noxious plants. We also advised national and European authorities on regulation regarding the prevention and management of invasive alien plants, and on the import and release of biological control organisms. The SMARTER approach may hence provide a template for trans-national and trans-sectoral cooperation in assessing socio-economic costs of noxious plants and their management, and in implementing and evaluating control measures against them.

Appendix A: Table 1. Old World (Afro-Eurasian) noxious plants that impact various sectors and regions making them suitable targets for future interdisciplinary management

Plant species	status	Sectors affected	Input from weed science	Input from plant invasion science	Expected benefits from synthesis *
Ageratum conyzoides L.	IAP	agriculture, environment, human/ animal health	practical advice for managing at crop field level; management by soil tillage/mulching/herbicide	natural and anthropogenic habitats; knowledge on invasion history and impacts	1, 10
Parthenium hysterophorus L.	IAP	agriculture, human/animal health,environment	practical advice for management at field scale to end-users	present and invasive in a variety of habitats; classical biological control	1, 2, 3, 4, 5, 7,8,10,12,13
Reynoutria japonica Houtt.	IAP	environment, engineering, agriculture (forage crops)	knowledge of species biology/herbicide efficacy; practical advice for handling of contaminated soil	knowledge on genetics, ecology and species interactions; policy support regarding IAS management in Europe (biocontrol)	1, 4, 5, 8, 12, 13
Eichhornia crassipes (Mart.) Solms	IAP	agriculture (rice), environment, trade	Management at crop field level	management at water body level, classical biological control	1, 3, 4, 5, 6, 8, 12, 13
Datura stramonium L.	crop weed/ IAP	agriculture, human/animal health	crop competition/rotation management at field crop and vegetable crop level	natural and anthropogenic habitats	10
Echinochloa crus-galli (L.) P. Beauv.	crop weed/ IAP	agriculture, environment	practical advice for management at crop field level; paddy rice, maize and summer crop fields	impacts on communities/ ecosystems in wetlands	10
Cyperus esculentus L.	crop weed/ IAP	agriculture, environment	green manure to increase competition and shading, with early and repeated tillage	coordinated management interventions across habitats and stakeholders	1, 3, 4, 5, 11
Cirsium arvense (L.) Scop.	crop weed	agriculture, environment	long tradition of management in native range, research at national research institutions	knowledge of species interactions, research at universities	1, 7, 9

Rumex spp.	crop weed	agriculture, environment, human health	local management; long tradition of management in native range, research at national research institutions	knowledge of species interactions, research at universities; classical biological control	2, 7, 9, 11, 12, 13

* **1** Developing habitat-specific management recommendations/solutions, based on various tools, **2** Considering the regional and local societal and economic environment, **3** Trans-national and trans-sectoral coordination, **4** Trade regulation and legal and regulatory aspects to support policy, **5** Interdisciplinary, **6** Reconciling different stakeholder interests, **7** Reconciling different management objectives, **8** Develop classical biological control options for a sustainable management, **9** Develop biocontrol products together with industry, **10** Develop horizontal integration of control across different weed species, **11** Develop vertical integration by combining different control measures against a specific target species (e.g. low herbicide dosage with a biocontrol product), **12** Efficient knowledge and technology transfer, **13** Economic assessment of weed impact and management evaluation;