Management options for the conservation of rare arable plants in Europe

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Abstract

Rapid intensification of farming after 1950 resulted in a dramatic decline in plant species diversity in European arable ecosystems, and pronounced shifts in species composition, including severe decreases in many species closely adapted to traditional agricultural practices. These changes in the arable vegetation have also resulted in pronounced losses of food and habitat resources for the dependent fauna. To counter these trends, and to conserve traditional arable plant communities, various strategies have been developed, ranging from an integration of conservation aspects into existing farming systems with a focus on crop production ('land sharing strategies') to 'land sparing' measures where conservation aspects take priority over crop production.

This review gives an overview of those strategies, with a particular focus on arable plant conservation. Among the systems integrating species conservation into regular crop production, good results were achieved with organic farming and traditional 'low-intensity farming systems'. Where production-focused management cannot deliver rare species persistence, targeted conservation measures are required. A wide range of such measures is available e.g. in the form of conservation headlands, uncropped cultivated field margins, and wildflower strips, and in the form of arable reserves and fields primarily managed for conservation objectives. Finally, we discuss the possibility of re-introducing rare arable species at suitable sites, highlighting the importance of favourable management for successful establishment, based on existing experimental evidence.

Keywords: arable reserve, biodiversity, conservation headland, decline, *ex situ* conservation, integrated farming, low-intensity farming, organic farming, re-introduction, set-aside, species traits, weeds, wildflower strip

I. Introduction

With the "invention" of arable farming some 12,000 years ago and the associated introduction of regularly-recurring soil disturbances (Barker 2009), suitable habitats were created both for annual crops and for non-crop species with similar niche requirements (Willcox 2012). With the global expansion of arable farming, together with cultivated species, these non-crop species were spread beyond their native distribution range (Dekker 2011). At least 11 different regions in Asia, Africa and America are believed to be independent origins of agricultural land use (Diamond 2002). With reference to these processes, and based on biogeographic and historical criteria, three types of geographic areas can be distinguished. The first type is comprised of those regions where arable farming first originated, and where most arable non-crops plants can be considered indigenous. The second includes regions in Europe, Asia and northern Africa, where the majority of arable species are non-native but their introduction occurred thousands of years ago, and they now represent an integral element of the vegetation within the cultural landscape (Willerding 1986; Preston, Pearman, and Hall 2004). The third comprises large parts of America, southern Africa and Australia, where arable farming is relatively recent, and the arable flora is largely comprised of non-native species introduced more recently from other parts of the world.

This categorization into native distribution areas, areas with a non-native but long-established arable flora, and more recently colonized regions, has important implications for the potential relevance for arable plant conservation. Most important are those regions where arable species are native and where, due to the degradation of natural habitats, arable fields represent an important secondary habitat for rare endemic species. The intensification of arable land use poses a growing threat to the survival of such apophytic species in their secondary habitats. This is for example the case in Turkey (Türe and Böcük 2008), Tajikistan (Nowak et al. 2014) and Oman (El-Sheikh 2013). This transition of rare species beyond their original habitats into arable fields has not just occurred in the original centres of agriculture. Other examples include species from coarse-sand habitats in northwestern Europe, such as *Arnoseris minima* (L.) Schweigg. & Körte (Sissingh 1950). In regions where arable species arrived long ago, they have already undergone hundreds of generations of selection to their new environment. Therefore, it is likely that distinctive regionally-adapted ecotypes have evolved (Vigueira, Olsen, and Caicedo 2013; Thomann et al. 2015). Such adaptation may not only have occurred in plants, but, due to functional relations, also in associated fauna such as pollinators, avifauna and other groups of organisms linked to the arable flora. By supporting ecological services such as insect pollination (Gabriel and Tscharntke 2006), soil conservation (Weil 1982), food and habitat provision for natural enemies of pests (Schellhorn and Sork 1997; Nentwig, Frank, and Lethmayer 1998), and the provision of aesthetic and social ecosystem services, arable plants have also benefited human wellbeing. For all these reasons, the rationale for conservation of the arable flora is more evident in regions where arable plants, although introduced, have been long-established, compared to regions where arable farming has been introduced more recently. However, even in regions where arable land use started only a few centuries ago, such considerations are reasonable because there, too, arable plants provide ecosystem services, and rare and native species may inhabit arable fields.

Until the 20th century, weed control was largely limited to cultural methods, including inversion tillage, hoeing, rotational grazing and the planting of long-straw cereals (e.g. rye). Then, the innovation of seed-drilling in rows enabled weed control by harrowing (Timmons 2005), and improved seed cleaning resulted in the decline of speirochorous species, i.e. species regularly re-introduced into fields as contaminants of crop seed (Kornaś 1988). Over the course of the 20th century, synthetically produced herbicides and fertilizers radically changed the situation, enabling much more efficient weed control, more densely-planted and more competitive crops, and narrow rotations made up of just a few profitable crops. In

cereal cultivation, shifts occurred from spring cereals towards winter cereals (Hald 1999a; Takács-György and Takács 2012), as well as towards earlier cultivation of cereal stubble (Pinke and Pál 2009). With the rise of chemical weed control, inversion tillage by means of ploughing was frequently replaced by reduced non-inversion tillage, or even no tillage (Chancellor, Fryer, and Cussans 1984; Cannell 1985; Morris et al. 2010).

In parallel with such management intensification at the field-level, the mechanization of agriculture also required an adaptation of landscape structures in the form of land consolidation. This also affected provision of a range of ecosystem services dependant on arable plant diversity, such as pollination and biological control (Landis, Wratten, and Gurr 2000; Marshall et al. 2003; Tscharntke et al. 2005; Bianchi, Booij, and Tscharntke 2006; Parish et al. 2009; Garibaldi et al. 2011).

Collectively, these changes had detrimental effects on the species diversity of the European arable flora, with many of the plant species typically inhabiting arable fields having severely declined in recent decades. Presently, 35% of plant species typically inhabiting arable fields are threatened in Germany (Korneck and Sukopp 1988), and 28% in Britain (Stroh et al. 2014), with the arable flora being 'the most threatened group of plants today' in Britain (Still and Byfield 2007). In the Netherlands, 20% of arable species growing on nutrient-rich non-calcareous soils, 42% of those growing on nutrient-poor non-calcareous soils, and a remarkable 88% of those typically inhabiting calcareous soils are red-listed (Sparrius, Odé, and Beringen 2012). As documented by a wide range of studies from various countries (e.g., Austria: Ries 1992; Croatia: Hulina 2005; Czech Republic: Kropáč 1988; Lososová 2003; Denmark: Andreasen, Stryhn, and Streibig 1996; Finland: Erviö and Salonen 1987; France: van Calster et al. 2008; Fried et al. 2009; Cambecèdes, Largier and Lombard 2012; Germany: Albrecht 1995; Meyer et al. 2013a; Greece: Bergmeier and Strid 2014; Hungary: Toth, Benecs-Bardi, and Balazs 1999; Pinke et al. 2011; Poland: Bomanowska 2010; Portugal: Moreira et al. 1996; Slovakia: Májeková et al. 2010; Spain: Cirujeda, Aibar, and Zaragoza 2011; Turkey: Türe and Böcük 2008; United Kingdom: Sutcliffe and Kay 2000; Wilson and King 2003, Potts, Ewald, and Aebischer 2010), these changes had deleterious effects on species diversity in general, and in particular on the rare species of the European arable flora. For an overview, see also Storkey et al. 2012 and the more recent meta-analysis by Richner et al. 2015.

Several of these studies discuss how rare arable plants could be effectively conserved, however, knowledge on this subject is still scattered and insufficiently documented. Therefore, our review aims to sum up the available information, focusing on the following questions:
-   What are the specific characteristics of rare arable plant species?
-   What are the underlying reasons for their decline?
-   Can production-focused farming systems benefit their conservation?
-   What are the merits of approaches specifically targeted at rare arable plant conservation?

Nomenclature of plants follows version 1.1 of the *The Plant List* (2013).

II. Specific characteristics of rare arable plants

The most common approach for evaluating the conservation value of species is their rarity which is usually reflected in their red-list status. However, arable plants are traditionally under-represented in red lists, e.g. in southern Europe, because they are non-native and depend on the maintenance of man-made habitats (Storkey et al. 2012). Nonetheless, arable plants colonized European landscapes earlier than 'natural elements' such as *Fagus sylvatica* (the spread of which may have also been decisively favoured by human land use

(Magri 2008)). Considering this status and their key functions in agroecosystems, such as habitat or food provision for beneficial fauna (Franke et al. 2009; Rollin et al. 2016), the inclusion of rare arable plants in such lists seems justified. Recent studies on the threat to segetal species in southern and southeastern Europe (Hulina 2005; Pinke et al. 2011; Rotchés-Ribalta et al. 2015a) indicate an increasing awareness of the issue there.

One approach with respect to the ecological processes affecting the rarity of a species is to investigate patterns at the level of functional traits. Knowledge of such functional traits may be useful to develop management tools which particularly select for traits of rare species while reducing more common or pernicious weeds. In this context, a key question is: 'How do rare arable species differ from more common ones on a functional level?' Storkey, Moss, and Cussans (2010) identified three functional groups of arable plants harbouring above-average percentages of threatened species. The first group includes tall, late-flowering species with large seeds, such as *Agrostemma githago* and *Bromus secalinus.* As these 'crop mimics' depend on regular reintroduction to fields as crop seed contaminants, they have been negatively affected by improved seed cleaning. Members of the other two types are characterized by late flowering, a short stature and production of large seeds. The authors argued that one advantage of having such large seeds may be the ability to allocate more resources to roots, providing a competitive advantage in more nutrient-limited situations. In traditional arable farming, such nutrient limitation was quite common. A well-developed root system in combination with a short stature, however, is only of advantage if aboveground competition is limited. With the introduction of artificial fertilizer, such nutrient stress was effectively alleviated, and increasingly intense crop competition may have particularly affected more stress-tolerant arable species. In their analysis of trait syndromes of rare arable species in Hungarian cereal fields, Pinke and Gunton (2014) also included life-form traits, based on an extended Raunkiaer classification which splits annuals into four distinctive groups according to timing of emergence. They found that rare arable species of cereal fields tended to combine low nitrogen requirements, germination in late winter or early summer, and short flowering periods.

A cytological study by Verlaque and Filosa (1997) suggested that rarity of arable species is also related to their genetic constitution. They found that most of the rare arable plants occurring on limestone soils in southeastern France were diploid, and members of small genera with low genetic variation. In contrast, polyploid species usually had a higher competitive ability, a broader ecological amplitude, and a wider distribution range.

III. Causes of the decline of rare species

Several factors have contributed to the great changes in the arable flora over the last 60 years. In literature, various investigations have highlighted the important role of herbicides in the decline of non-crop species richness in arable fields (Rydberg and Milberg 2000; Hyvönen and Salonen 2002; José-María et al. 2011). However, as shown by comparative studies involving pairs of closely-related rare and common arable species, herbicide sensitivity usually tends to be equally pronounced in both members of a given species pair, indicating that rarity *per se* may not necessarily be the result of herbicide sensitivity (Wilson 1990; Egan, Graham, and Mortensen 2014; Rotchés-Ribalta et al. 2015b).

Other characteristics such as phenological avoidance of herbicide exposure may also affect whether a species is affected by herbicide application. Prior to the widespread use of herbicides, early germination at low temperatures may have provided winter-annual species with a developmental advantage, since competition for light and nutrients is low at this early stage. However, with the advent of herbicides, early germination turned into a disadvantage, as the same species were now particularly exposed to herbicide application. In contrast, summer-annual species requiring higher germination temperatures are better able to avoid

herbicide exposure, and may even benefit from reduced competition. Thus, relating intensity of chemical weed control in 218 winter wheat fields in France to the weed community-weighted mean date of emergence clearly showed that late emergence allows species to avoid herbicide pressure (Fried, Kazakou, and Gaba 2012). Furthermore, winter annuals also tend to produce fewer and larger seeds than summer annuals (Bekker et al. 2003). As winter annual communities also include higher percentages of character species with a low seed bank persistence than summer annual assemblages (Thompson, Band, and Hodgson 1993; Bekker et al. 2003), a quicker exhaustion of buried seed reserves can be expected (Storkey, Moss, and Cussans 2010) if reproduction is prevented by weed control. In agreement with such mechanisms, Maillet and Godron (1997) found that the species which disappeared from fields in the Languedoc (S France) from 1932-1968 to 1980 usually germinated in autumn, flowered early and produced short-lived seeds. Otte, Bissels, and Waldhardt (2006) found that the species which increased in arable habitats in recent decades tend to be characterized by relatively high temperature optima for germination. Similarly, Pinke and Gunton (2014) ascribe the rarity of late-winter and early-summer annuals to the fact that the timing of their emergence may make them more susceptible to early-season herbicide application, characteristic of intensive cereal farming.

In addition to increased weed control efficiency, agricultural intensification also created higher levels of crop competition for the unsown arable flora. The contributing factors were (1) increased use of fertilizers, (2) development of more competitive crop varieties capable of converting increased nutrient availability into biomass production, (3) shortening rotations to a few highly competitive crops, and (4) a trend towards sowing crops more densely, made possible by the alleviation of nutrient limitation by fertilizer. As most plant species achieve maximum biomass with comparatively high nutrient supply in monoculture ('physiological optimum'), such negative effects of increased fertilization on the unsown arable flora appear not reasonable. However, in multispecies communities, more stress-tolerant component species may reach maximum biomass at much lower nutrient levels ('ecological optimum') (Austin and Austin 1980). This principle also applies to rare arable plants. In low-competition environments, e.g. in the absence of crops, many of these species potentially benefit from fertilizer application (see Table 1), whereas in the presence of highly competitive crops or weeds, they may suffer from increased competition. Many rare species are characterized by a short stature (Storkey, Moss, and Cussans 2010), which makes them particularly susceptible to the high levels of shading brought about by cereal canopies in intensive agricultural systems (Kleijn and Van den Voort 1997). However, as shown in experimental studies (Table 1), not all rare arable species are highly sensitive to increased crop competition due to fertilizer application.

Another factor which has affected rare arable plants from the beginning of the 20th century is improved seed cleaning. The development of threshing machines and combine harvesters in conjunction with specific seed-cleaning devices led to a move away from farmers using their own seed from previous year's crop towards purchasing seed from commercial producers. This development interrupted the dispersal of 'crop mimic' species which evolved seeds of similar size and shape, in order to ensure being harvested and spread along with the crop seed (Kornaś 1988). Many such species almost disappeared subsequent to the introduction of efficient seed cleaning and the commercialization of crop seed production and distribution (e.g. Kornaś 1988; Meyer et al. 2013b). Similarly, reduced cultivation of certain traditional crops also decreased rare arable plants. Thus, *Camelina alyssum*, *Cuscuta epilinum*, *Lolium remotum*, *L. temulentum*, and *Silene linicola*, which all are closely adapted to the specific living conditions in flax, almost disappeared from Central Europe when cultivation of flax was discontinued (Meyer et al. 2013b), and *Illecebrum verticillatum* significantly declined in Poland when traditional root crops were replaced by maize (Skrajna, Kubicka, and Rzymowska 2012).

In Hungarian fields, Pinke et al. (2009) found undisturbed stubble after harvest boosted seed production particularly of late-flowering species, and provided especially valuable habitats for threatened species such as *Stachys annua* which are known to perform best when stubble ploughing is postponed until late autumn (Pinke and Pál 2009). In French arable fields, Pointereau, Coulon, and André (2010) similarly observed that both chemical and mechanical cultivation of stubble immediately after harvest disrupted the reproduction cycle of the rare species *Thymelea passerina, Stachys annua, Nigella gallica, and Delphinium verdunense.* Another change in soil cultivation which severely affected rare arable plants is the increased intensity and depth of soil tillage. This development particularly affected bulbous geophytes like *Gagea villosa*, *G. pratensis*, *Ornithogalum umbellatum*, *Allium* spp., or *Muscari* spp. (Meyer et al. 2013b).

Drainage, which is widely recognized as a major reason for biodiversity losses in wetlands, is often overlooked in the context of arable plants. However, as recently shown by Altenfelder, Raabe, and Albrecht (2014), threatened plants of waterlogged arable field depressions, such as *Elatine alsinastrum* or *Juncus tenageia*, may be even more affected by a lack of temporary flooding than by herbicide application. Most such species can avoid herbicide application through late germination. One notable exception is the winter annual *Myosurus minimus* whose historic decline was effected by drainage (Salisbury 1961), but which, due to its early-seasonal phenology, is also highly sensitive to herbicides (Altenfelder et al. 2016). The importance of temporary flooding for rare arable species is also underlined by recent records of the Characeae species *Chara baueri* in temporarily inundated fields in Brandenburg, Germany (Raabe 2009). Worldwide, there has only been one record documented for this species before. It was outside of arable fields, in western Siberia. As illustrated by *Armeria arcuata* (Moreira et al. 1996), drainage for irrigation can even result in local extinction of endemic arable plants.

A newly developing threat to endangered arable plant species may be the effects of climate change, e.g. due to altered water availability. Using confamilial pairs of species, Rühl et al. (2016) showed that a reduction in water potential affected the germination of endangered arable species more than paired common arable species.

In addition to such management intensification at the field-level, significant changes also occurred on the landscape scale, where structures were adapted to meet new operational requirements associated with the introduction of modern machinery. There, land consolidation in particular has led to a tremendous loss of field margin areas which provided favorable habitats for rare arable plants (Stoate et al. 2001; Robinson and Sutherland 2002; Fried et al. 2009; Storkey et al. 2012; Solé-Senan et al. 2014; Rotchés-Ribalta et al. 2015c). Land abandonment and conversion to other forms of land use like forestry or grassland (Stoate et al. 2001; Roche and Tatoni 2001; Dutoit et al. 2003; Storkey et al. 2012) also played a role. Beyond these direct losses of suitable habitat, indirect effects, e.g. via increased habitat fragmentation, have also affected the survival of rare species populations (Brütting et al. 2012; Le Corre et al. 2014).

As illustrated in this section, the main cause of the observed decline of rare arable plant species are changes brought about by intensive agriculture, in particular due to more efficient weed control, e.g. by herbicides, and increased crop competition, e.g. from fertilizer application and the use of more competitive crops which may be planted more densely than previously. In addition, changes in land use type and the landscape structure exacerbated this trend. Thus, to create conditions ensuring the long-term persistence of these traditional arable species, we have to develop tools which integrate species conservation into modern farming practice. Several approaches exist that may facilitate such a shift either at the farm-level (e.g. organic or integrated farming) or at smaller spatial scales (e.g. field reserves or conservation measures targeted at arable field margins).

IV. Conservation strategies at the farm scale

The disparate objectives of biodiversity conservation and agricultural production can be reconciled in two different ways: The 'land sharing' strategy integrates biodiversity conservation with food production on the same land, using methods which – in our case – should also benefit rare arable plants. In 'land sparing' strategies, conservation areas are separated from croplands, with high-yield farming facilitating the protection of remaining natural habitats from agricultural expansion (Phalan et al. 2011). These strategies are not mutually exclusive, and practice will usually fall somewhere on a gradient between these two ideal concepts (Fischer et al. 2014). In this section, we discuss land sharing strategies, i.e. farming systems where the main objective is to produce agricultural goods but which also consider the preservation of environmental resources, including arable biodiversity. Multiple objectives can be achieved by adopting management approaches which aim to reconcile crop production aspects with conservation aspects over the whole area, as realised in organic or in integrated farming systems.

Organic farming is characterised by the prohibition of synthetically-produced pesticides and fertilizers (Stolze et al. 2000). Dispensing with such agrochemicals tends to increase non-crop plant diversity, both through the prohibition of herbicides which are the most efficient instrument for weed control in conventional farming, and through lower nutrient levels, resulting in reduced crop competition (Alfoeldi et al. 2002). The restrictions associated with organic farming have far-reaching implications in practice, meaning that control of agriculturally relevant weeds is carried out mostly via ploughing, currying, and the use of diverse crop rotations, which also include cultivation of cover crops. Sowing such cover crops can be particularly effective, but it affects populations of more desirable non-crop species, both through competition and, e.g. in the case of grass-clover leys, prevention of reproduction by mowing and grazing. Over the course of a one-year grass-clover ley, in the absence of replenishment, soil seed bank densities of arable species can decline by as much as a third (Albrecht 2005). On the other hand, the more diverse crop rotations used in organic farming provide more suitable living conditions for arable plants.

Overall, organic farming tends to be associated with a higher plant species diversity in arable fields (Moreby et al. 1994; Frieben and Köpke 1995; Becker and Hurle 1998; Hald 1999b; Kay and Gregory 1998, 1999; Rydberg and Milberg 2000; Hyvönen et al. 2003; Hole et al. 2005; Bengtsson, Ahnström, and Weibull 2005; Gabriel et al. 2006; Hotze and van Elsen 2006; Gibson et al. 2007; Albrecht et al. 2008; Kolářová, Tyšer, and Soukup 2013a). However, as targeted application of specific measures can result in efficient 'weed control' also in organic farming, some studies found no such positive effects (Weibull, Ostman, and Granqvist 2003).

Both in organic and conventional farming, frequencies of threatened arable plants are usually low. However, overall, organic farming tends to provide a more suitable environment for such species. In a survey of rare arable plants both in conventional fields and in organic fields in the south-east of England, Kay and Gregory (1998, 1999) found that organically-managed fields supported a wider range of rare arable species, as well as larger populations of individual species. In this study, out of 21 'target species' eleven were found exclusively on organic farms. Another eight occurred on both types of farm, but tended to be more common on organic farms. Four species found exclusively on organic farms – *Galeopsis angustifolia*, *Ranunculus arvensis, Valerianella dentata,* and *Spergula arvensis* – are priority species under the UK Biodiversity Action Plan (BAP). In contrast, no BAP species, and only two other 'target' species (*Anisantha diandra* and *Geranium pusillum*), were found exclusively on conventional farms. In a Swedish study, Rydberg and Milberg (2000) found the red-listed species *Consolida regalis* and *Buglossoides arvensis* exclusively in organic fields. In

Germany and Austria, Callauch (1981), Plakolm (1989), van Elsen (1989), Wolff-Straub (1989) and Frieben et al. (2012) compared numbers of endangered species in organic and conventional fields, all finding higher numbers of such species in organic systems. In a survey based on 290 relevés in the Czech Republic, the sum of frequencies of endangered arable species in organically managed fields was 4.5 times higher than in conventional farming (Kolářová, Tyšer, and Soukup 2013b). In the Mediterranean, in Catalonia, Rotchés-Ribalta et al. (2015a) found a whole range of threatened non-crop species in organically managed fields. Frequencies of the majority of these species were low, and occurrence appeared to be more determined by management history of fields and the local field- and farm-level species pools rather than actual farming practices, although individual species were also affected by management practices. In the same region, a comparative study by Romero, Chamorro, and Sans (2008), found nine out of eleven arable species classified as rare only occurred on organic fields, albeit at low frequencies. Similarly, Armengot et al. (2011) found the rare species *Bifora testiculata* and *Kickxia spuria* only on organic farms. In a recent study comparing new data with historical references, Chamorro, Masalles, and Sans (2016) observed that cover of rare species was significantly higher in fields managed organically for about a decade than in conventionally managed references. However, numbers and cover of rare species in organic fields had significantly declined compared to the levels recorded between 1953-88.

However, not all threatened species clearly benefit from organic farming. Accordingly, after conversion of a whole farm from conventional farming to organic farming, Albrecht and Mattheis (1998) found significant increases only in two rare species (*Legousia speculum-veneris*, *Sherardia arvensis*), whereas no significant change was observed for *Cyanus segetum*, *Myosurus minimus,* and *Veronica triphyllos*. A detailed investigation of why *V. triphyllos* failed to benefit from this conversion highlighted an important role of species-specific life strategies and dispersal limitations (Albrecht, Mayer, and Mattheis 2000). In the study area, *V. triphyllos* mainly occurred on sandy soils restricted to small hilltops. A persistent seed bank represents a good adaptation to summer drought at these sites. As a winter annual that germinates at low temperatures in autumn and completes its life cycle in late spring, *V. triphyllos* phenologically avoids such summer droughts. After introduction of organic farming, the species showed a slight increase on one hilltop where it already occurred, but was unable to colonize a similar habitat located only 80 m away. Analysis of possible dispersal vectors showed that early seed-shed in this species makes seed transfer by harvesting machinery unlikely, and that dispersal is further limited by the low amounts of sandy soil actually sticking to tyres and soil working implements. Thus, *V. triphyllos* is a good example showing that even when potentially favourable conditions for growth and reproduction are restored, factors such as habitat fragmentation and poor dispersal can limit long-term recovery of threatened plants in agro-ecosystems (Mayer and Albrecht 2008). The effects of dispersal limitation on population dynamics of rare arable species and on their capacity for re-colonization have also been previously discussed by Bischoff (1999, 2005).

Overall, the majority of studies such as those listed above illustrate a clear potential for organic farming to benefit rare arable plants, suggesting that an expansion of organic farming could help prevent further decline. However, even in organic systems, management intensity plays a role, and intensive currying or cultivation of grass clover in such systems may be as harmful to threatened species as herbicide application is in conventional systems. Such practices should thus be limited to a minimum if management objectives for a given field include preservation of rare arable plants.

Integrated farming aims to deliver sustainable agriculture with the careful use of resources (EISA 2012). To this end, use of pesticides and fertilisers is minimized by improved targeting and integration with cultural control methods for weeds, pests and diseases (Boatman et al. 2007). In a review of eight studies of the effects of 'integrated farm management' (IFM) on

plant species diversity Berry, Ogilvy, and Gardner (2005) found in every single one significantly higher levels of diversity under IFM than in conventionally-managed references. In these studies, IFM generally involved reduced herbicide application, and in most studies also reduced use of N fertilizer; however, no rare species occurred. Similarly, in the TALISMAN study (Squire, Roger, and Wright 2000), reduced application of nitrogen fertilizer and a 50% decrease of herbicide application resulted in markedly increased species richness in the soil seedbank after five years, however with considerable variation depending on crop sequences. Again, focus of the study was more on general species richness, rather than on rare species. However, as shown by other studies, total species richness and occurrence of rare species typically show similar patterns (Sutcliffe and Kay 2000; Walker et al. 2007). Thus, results of the above-mentioned studies may nonetheless suggest that, compared to conventional management, integrated management may provide more suitable conditions for threatened species. Having surveyed over 100 fields in Scotland, Hawes et al. (2010) found that, despite species richness at the field level being highest on organic farms, integrated farms tended to have even higher species richness at farm and landscape scales, due to greater variation of crop types and of cropping practices between fields.

On arable land prone to soil erosion or summer drought, farmers frequently incorporate conservation tillage into IFM, to ensure sustainable management of soil resources (Randall and James 2012). In these cases, ploughing is usually substituted by non-inversion tillage using cultivators or roto-tillers. This practice is frequently accompanied by an accumulation of seeds at the soil surface (Albrecht and Sprenger 2008) and increased densities of non-crop plants (Cousens and Mortimer 1995; Grundy, Mead, and Bond 1996), necessitating more efficient weed control measures.

To minimize soil erosion, reduced tillage was also introduced to fields under integrated management at the FAM Research Station in Scheyern, Bavaria, where weed control measures were applied on the basis of economic thresholds (Auerswald et al. 2000), in accordance with models adapted from Gerowitt (1992) that were based on relationships between crop yields and densities of non-crop plants. Over the first five years, species diversity significantly increased, but this was followed by a decline to levels even lower than those observed at the outset. This decline was the result of having to increase the number of herbicide applications per year, from one to several, and of having to apply highly-efficient compounds, in response to a strong increase in overall weed densities. In line with this decline, a population of the red-listed winter annual *Legousia speculum-veneris* also declined below its initial size. However, *Sherardia arvensis*, another species threatened in large parts of Central Europe, significantly increased (Albrecht and Sprenger 2008). Seemingly, this late-germinating species (Schneider, Sukopp, and Sukopp 1994) was much less affected by herbicide application, and may have benefited from reduced tillage operations after harvest. Other studies carried out in Norway, found abandonment of regular ploughing resulted in increased establishment of perennials and of winter annuals, at the expense of highly specialized spring annuals (Tørresen and Skuterud 2002; Tørresen 2003).

In the traditional **low-intensity farming systems** described by Beaufoy, Baldock, and Clark (1994) intensification of arable land use is usually unprofitable due to extreme soil conditions or a difficult topography. Such systems are particularly significant in the Mediterranean drylands of Spain, Portugal, Italy and Greece, but they also occur in southern France, Hungary and Poland (Beaufoy, Baldock, and Clark 1994; Stoate et al. 2009). In contrast to organic and integrated farming, these systems are not based on clearly defined regulations but on traditional management practices which have evolved over time in adaptation to local site conditions. Fields are often small and farming is characterized by alternating cultivation of cereals which are usually fed to the farmers' livestock and years in which fields remain uncultivated and become part of the pastoral land. Occasionally, leguminous crops are grown to improve soil fertility. In southern France, farmers frequently use seeds from the

preceding crops for sowing, which facilitates dispersal of seed impurities, including the seeds of segetal species (Loddo et al. 2009; Pointereau, Coulon, and André 2010). This combination of extensive management, temporary set-aside, zoochorous seed dispersal by sheep and goats, and a small scale landscape mosaic with a great diversity of field margins and boundary structures results in habitats with a great potential for the persistence of rare arable plants (Gaba et al. 2010; Fried et al. 2009; Pointereau, Coulon, and André 2010). An extraordinary importance of such habitats for the occurrence of rare arable plants was also documented for Hungary (Pinke et al. 2009) and for mountainous regions of Central Italy (Pál et al. 2013). Recently, this type of arable land use is experiencing a dramatic decrease. Pinke (pers. comm.) reported that almost all such species-rich habitats of rare arable plants in Western Hungary which had been described in Pinke et al. (2009), were recently lost due to intensification or abandonment.

Generally, organic and integrated approaches to farming as well as low-intensity farming systems tend to boost species diversity both of common and rare non-crop plants. However, in these approaches, conservation objectives remain subsidiary to the main purpose of food production, and thus, there is a latent incentive for farmers to shift the balance between conservation and crop production towards the latter. Therefore, considering the growing demand for food and arable products, conservation of particularly sensitive species in agricultural landscapes may require more targeted measures and prioritization of the conservation aspects on at least part of the area under cultivation (Law et al. 2015). One way to achieve this is by segregation within fields of production-focused areas and conservation-focused areas.

V. Conservation measures targeted at field margins

In this section, we discuss conservation measures specifically targeted towards arable field margins, aiming to promote rare arable plants. Thus, whilst crop production remains the main management objective at the level of whole fields, conservation aspects are given priority in their margins. According to the classification given in chapter V, this approach can be assigned to the land sparing conservation strategy. In Europe, such measures are commonly integrated into conventional farming systems via agri-environment schemes (AES), which can also be an element of organic and integrated farming systems. The most widely known measures are conservation headlands, i.e. cropped field margins with restricted agricultural inputs, and other options including uncropped field margins and wildflower strips, all of which will be discussed in this section. We also briefly discuss the set-aside measure, an AES which was previously promoted by European agricultural policy but has since been discontinued.

Conservation headlands have first been trialled in Germany where they are referred to as 'Ackerrandstreifen' (= 'field margin strips'; Schumacher 1980). AES are usually designed at national or regional levels, and participation by farmers is voluntary. They provide payments for specific management measures designed to produce environmental benefits. In the case of measures primarily targeted at rare arable plants, the focus is often specifically on field margins. This is partly because such an approach is more practicable for farmers and helps minimize crop losses (Smallshire and Cooke 1999), but also because, particularly in conventionally-managed fields, margins tend to support higher overall plant species richness (Marshall 1989; Romero, Chamorro, and Sans 2008) as well as higher incidence of rare arable species (Wilson and Aebischer 1995; Fried et al. 2009), compared to the interior of fields. This is due to arable plants in field margins benefiting from increased light availability and reduced management intensity (Kleijn and Van der Voort 1997; Marshall et al. 2003). In the German 'Ackerrandstreifenprogramm' (Schumacher 1980), such 'edge effects' were further enhanced by a ban of herbicide application and a reduction of fertiliser inputs in field margins signed up to the program. Successful pilot studies led to more widespread adoption

of these measures, and subsequently, the majority of German federal states introduced similar programs. A peak was reached in the early 1990s, when a total area of more than 5,000 ha was managed as 'Ackerrandstreifen' (Wicke 1998). However, entry to these schemes was voluntary and unregulated, and thus, targeting of sites was poor. Therefore, many sites were included that lacked species assemblages worthy of protection. Nonetheless, in those federal states where fields were regularly surveyed and accurately selected for sites with a high species diversity, the schemes proved quite successful in preserving rare arable plants. So there were 49 species of Red Data Book status recorded in fields under agreement in Rhineland-Palatinate (Oesau and Jörg 1994), 45 in Lower Saxony (Schacherer 1994), 41 (including "vulnerable" species) in the southwestern North Rhine-Westphalia (Frieben 1995), and 23 in Upper Bavaria (Mattheis and Otte 1994). Some of the species found in these surveys were previously thought extinct in the respective region. The benefits of similar measures to the arable flora have also been documented for Switzerland, The Netherlands, Luxembourg, Sweden, the United Kingdom, Denmark, Slovakia and Hungary, as summarised in the bibliography by Meyer et al. (2013b). However, several reasons, such as weed infestations, difficulties with monitoring the compliance of farmers with prescriptions stipulated in their agreements, inflexible management agreements, insufficient financial support and difficulties with integrating such margins into the operational processes of farming led to a severe decline in the uptake of 'Ackerrandstreifen' options by German farmers from the 1990s onwards (Wicke 1998). A more recent survey carried out in Germany in 2007 showed that only 600 sites with a particularly valuable plant species composition remained in such schemes (Meyer and Leuschner 2015). Similar issues exist in the UK, where uptake of AES options designed for rare arable plants tends to be poor. For example in England, out of a total of 58,000 ha of arable land managed under the Entry-Level Stewardship scheme at the end of 2012, a mere 500 ha (i.e. less than 1%), were managed for rare arable plants (Clothier 2013), i.e. as conservation headlands or as **uncropped cultivated margins**. These margins are annually cultivated but no crops are sown and herbicide application is restricted. Locations of such uncropped cultivated field margins are either fixed for the duration of an AES agreement, or can be moved annually. In contrast, over 24,000 ha (i.e. > 40%) were managed mainly for the benefit of farmland birds (Clothier 2013). Reasons are manifold for the comparatively poor uptake by farmers of such field margin options for rare arable plants, including, amongst others, a deficit in farmers' awareness of rare arable species, low payment incentives for these specific measures, and farmers' concerns regarding weed infestations (Still and Byfield 2007). Such weed infestations can indeed develop relatively quickly e.g. on uncropped cultivated field margins (Critchley, Fowbert, and Sherwood 2006; Pywell et al. 2010). Recent research has addressed how this issue can be managed without overly impacting on populations of threatened species, e.g. by varying season or type of cultivation, or by applying selective herbicides specifically targeted at the pernicious weeds (Wagner et al. 2013; Moyse and Shellswell 2016). The use of selective herbicides has also been investigated as a tool for conserving arable plant diversity and rare species in cereal stands (e.g. Jones and Smith 2007; Ulber, Steinmann, and Klimek 2010).

In the UK, monitoring the success of AES field margins managed to promote rare arable plants has confirmed positive effects. Across a total of 156 such margins in England, Walker et al. (2006, 2007) recorded 34 rare arable plant species, amounting to 40% of the British rare arable flora. Thirty-nine percent of these margins supported populations of rare species, compared to only 15% of cereal crop controls. The most widespread arable species were *Euphorbia exigua*, *Legousia hybrida* and *Kickxia spuria*, each of which were found on ca. 8-9% of surveyed AES margins, and a further nine rare arable species were recorded on at least 2% of AES margins, including *Fumaria densiflora*, *Glebionis segetum*, *Papaver argemone* and *Silene noctiflora*. Four species (*Cyanus segetum*, *Fumaria purpurea*, *Scandix pecten-veneris*, *Silene gallica*) were BAP priority species. Uncropped cultivated margins were by far the richest in rare species, supporting significantly higher numbers than any of

the other types of margin included in the study, including non-AES controls (Walker et al. 2007). Within uncropped margins, 67% supported populations of one or more rare species, and four rare species (*Euphorbia platyphyllos*, *Fumaria vaillantii*, *Legousia speculum-veneris*, *Scandix pecten-veneris*) were exclusively found on this type of margin. Lower mean and total numbers of rare species were recorded on other AES margin types including uncropped spring fallow and two kinds of conservation headlands with restricted insecticide and herbicide use, one of which was with additional fertilizer restrictions, and one without. While mean numbers of rare species still tended to be somewhat higher in such options than in cereal controls, the differences were not significant (Walker et al., 2007). However, with the exception of conservation headlands without fertilizer restrictions, which tend to be characterized by high levels of crop competition (Kleijn and Van der Voort 1997), AES margins supported significantly higher total plant species richness than cereal controls (Walker et al. 2007).

Wildflower strips are not specifically aimed at conserving rare plants, but at providing habitat for agricultural fauna (Haarland, Naisbit, and Bersier 2011). The range of species usually sown comprises cover crops (e.g. *Phacelia tanacetifolia, Onobrychis sativa, Fagopyron tataricum*), non-native ornamentals such as *Malva mauritanica*, and wildflowers of native grassland (Kirmer et al. 2016). From a conservation perspective, the value of wildflower strips could be markedly improved if threatened arable species would be included. Including locally-sourced seed of rare arable species into wildflower mixtures would help to diversify habitat and food resources for fauna during the wildflower-strip phase, and may result in re-establishment of these species in subsequent crops. In experimental wildflower strips based on rare arable species, such species successfully set seed in the first year after sowing, and helped suppress populations of certain problem weeds (van Elsen and Hotze 2008). However, in the second year of this particular study, when strips were re-sown with winter wheat, most sown rare species declined, with the exception of the more competitive *Agrostemma githago* which attained abundances high enough to necessitate special cleaning of crop seeds (Hotze et al. 2009). In Switzerland, such mixtures based on traditional and rare arable species are already commercially available, with e.g. the 'UFA Ackerflora' being made up of regionally-sourced seeds of 32 arable species the large majority of which are red-listed for Switzerland. Studies by Eggenschwiler et al. (2007) and by Boerlin (2008) have indicated that with regular tillage, most species included in such mixtures persisted at sown sites for at least several years after sowing, doing particularly well in uncropped margins, as opposed to cropped headlands. In these experiments, most sown species achieved only low cover, usually below 2%, while more competitive species such as *Agrostemma githago*, *Cyanus segetum*, and *Papaver rhoeas*, achieved considerably higher cover. However, as with other conservation measures targeted at field margins, this Swiss approach suffered from low uptake by the farming community, e.g. due to perceived issues with problem weeds (Eggenschwiler et al. 2007). Similar introductions have been carried out as part of the long-running Cornfield Flowers project in North Yorkshire, England, in which, with involvement from volunteers, seeds of local provenance from a wide range of rare arable species were collected, propagated in nurseries, and then introduced into field margins on participating farms (Cornfield Flowers Project 2015).

Beyond these benefits to the conservation of rare arable plants, their inclusion in wildflower strips may also support the characteristic fauna of agro-ecosystems. Comparing mean individual abundances within various arthropod orders and within Coleoptera families across arable field plots sown with rare arable plants and plots sown with commercial mixtures of non-native wildflowers, Bonneville et al. (2015) found in many instances higher numbers of individuals in plots where arable species were sown.

Commonly-used wildflower seed mixtures often contain no rare arable species at all, although *Cyanus segetum and Agrostemma githago* are sometimes included for their

attractive flowers and their well-known benefits to pollinators. However, these are the only species used more widely, and seed provenances are often non-native, or at least non-regional, with potentially negative effects on existing local populations (Hotze et al. 2009). For *C. segetum*, this issue has been discussed in more detail by Wilson (2007a).

In their current form, mainly targeted at resource provision for the arable fauna, wildflower strips are of little benefit to the rare arable flora. However, as outlined above, there may be potential for reconciling both objectives by developing seed mixtures based on rare arable plants for such strips. However, further research is required with respect to the composition of appropriate seed mixtures and regarding suitable establishment methods. Amongst others, optimal relative proportions of threatened species in such mixtures, issues in relation to the propagation of autochthonous seed material, and the potential impacts of re-introduced populations of rare arable species on crop yields all require further attention.

Historically, another AES measure, **set-aside**, tended to be quite popular, but this measure has since been discontinued in European agri-environment schemes. Although it never had been expressly stated that the major issue of this instrument was to reduce surplus production of arable crops (European Council 1992), it also held out a prospect of environmental benefits. Set-aside meant that a farmer would take a certain percentage of their arable land out of production, which could either be in the same location for the full duration of an agreement, or on the basis of annual rotation around the farm. Uncultivated permanent set-aside tended to be associated with an initial increase in species diversity, followed by a decline. This decline is due to succession, where establishment of annuals is more and more suppressed, due to increasing dominance of perennial species (Osbornová et al. 1990; Wilson 1992). In a survey of 158 fields in Lower Saxony, covering a range of set-aside types, Waldhardt (1994) found 38 species listed in the Red Data Book of this German federal state. Most of these species were annuals, achieving their highest abundance in the 2nd year of set-aside. Accordingly, Albrecht (2004) detected threatened species in seed bank studies in one- to five-year old set-aside, but not on older set-aside. These result are in line with Dutoit et al. (2003) who found that resumption of cultivation after a ten-year set-aside period of a field in the Luberon area in southern France, a region known for its high arable plant species richness, did result in re-establishment of only very few segetal species from the soil seed bank. The authors thus concluded that species restoration based on re-activation from the soil seed bank may hold little prospect after extended periods of non-arable land-use. At this site, however, assessment of initial species composition was based on oral reports and on vegetation sampling in neighboring fields, rather than on actual historical records. In contrast to the above studies, Wäldchen, Pusch, and Luthardt (2005) and Kohler et al. (2011) both found that ploughing can successfully stimulate the emergence of rare species on former arable fields even decades after their conversion to grassland. In former arable fields which were sown to grass and clover 20 years ago, Chancellor (1986) also re-detected a small number of germinable seeds of *Glebionis segetum* and *Legousia hybrida*. This apparent contradiction may partly be due to the fact that, on the set-aside fields sampled by Albrecht (2004), seeds produced by initial cohorts of rare species' populations were not incorporated into the soil by tillage operations. Instead, they remained permanently exposed at the soil surface, where they may have experienced high rates of mortality, both due to fatal germination and/or exposure to seed predators and pathogens. In contrast, in the fields studied by Wäldchen, Pusch, and Luthardt (2005) and Kohler et al. (2011), regular tillage prior to conversion to grassland may have resulted in a build-up of initially very large seed reserves at a depth where seeds were no longer exposed to seasonally varying germination stimuli. Recent results by Saatkamp et al. (2011) provide further support for such an interpretation, illustrating the crucial role that such environmental variation plays in affecting germination patterns and long-term seed bank persistence of rare arable plants. For conservation management this means that long set-aside periods may least affect rare

arable plants in situations where seed reservoirs of these species in deeper soil layers may help ensure local persistence during the fallow period.

EC regulations also promoted set-aside measures which involved seeding a limited range of cover crops as an alternative to leaving fields uncultivated. However, Waldhardt (1994) and Tscharntke et al. (1996) showed that the sowing of grass-clover mixtures or of other competitive cover crops reduced arable plant diversity. Accordingly, Stoate et al. (2001) pointed out that the ecological benefits provided by such management remain well below those achievable with more appropriate management.

While conservation measures targeted at field margins not always easily reconciled with the overarching objective of crop production, they tend to be efficient means for conserving existing populations of rare arable plants. However, as they are usually administered through voluntary AES agreements of a limited duration, they may not represent the most optimal approach for providing efficient long-term protection of arable land characterized by particularly high levels of arable plant diversity, high numbers of rare species, or the occurrence of especially rare or threatened species. In such instances, prioritization of conservation over crop production may be required over the whole cultivated area, and safeguards may be required to ensure long-term protection.

VI. Conservation as main priority of field management

In **arable reserves**, conservation aspects are given priority over crop production across the whole area under management, thus avoiding potential conflicts between these objectives. Such reserves were first established in many European countries throughout the 1970s and 1980s. Some of these early reserves were set up in the context of open-air museums aiming to educate the public on traditional farming and rural life. An overview of these early efforts is given in Meyer et al. (2013b).

More recently, the ongoing decline of large parts of the traditional arable flora has led to renewed efforts to set up such reserves in various parts of Europe, inspiring the establishment of regional networks of these sites. For example, in the UK, this issue was approached by the development of a scoring system to identify highly valuable sites, based on the presence of a range of indicator species, to identify holdings classified as Important Arable Plant Areas (IAPAs), either at European, UK, or county level, with the aim of facilitating their long-term protection (Byfield and Wilson 2005; Wilson 2007b). To acknowledge the re-establishment possibility of 'lost' species from the soil seed bank once suitable management is re-applied (Wäldchen, Pusch, and Luthardt 2005; Kohler et al. 2011; Moyse 2013), Byfield and Wilson (2005) consulted records dating back to 1985 for a provisional analysis. They identified 105 sites as important at the UK level, six of which were also classified as important at the European level. However, the list of indicator species and the scoring system have since been modified, and an updated analysis based on the modified scoring system may produce different results (C. Shellswell, pers. comm.). A set of case studies in Wilson and King (2003) gives a background to some of the most important IAPA sites and their management. In Switzerland, a 'resource project for arable plants' was launched to identify priority areas for protection of the arable flora, with a total of 83 ha already being included in a growing network of sites (Schneider 2014). In France, the "Plan national d'actions en faveur des plants messicoles 2012 - 2017" (Cambecèdes, Largier, Lombard 2012) aims to elaborate indicators based on species richness and rarity to identify areas where such AES would be most suited. Based on these results, a new AES is developed to encourage farmers to maintain traditional low intensity farming practices. This AE measure especially focuses on areas of rare arable plants where extensive farming is threatened by intensification or abandonment. One advantage of such conservation schemes is that their focus tends to be on the preservation of regionally distinctive arable plant

assemblages s, including a reliance on regional plant material in any re-introduction efforts, as opposed to using other provenances, which used to be common place in some arable reserves (Meyer et al. 2013b).

In Germany, the '100 Fields for Biodiversity' project was launched in 2009 to set up a network of important arable sites characterised by a rich arable flora supporting rare and threatened species, and to ensure permanent protection of these sites by securing long-term management conducive to this aim. Unlike earlier approaches, this project aims to develop locally-adapted concepts for ensuring long-term financial support, regular monitoring of the vegetation, and participation of farmers in the development and implementation of management and the resolution of conservation issues (Meyer and Leuschner 2015). For 25 of the rare arable species protected by this network of sites, Germany holds responsibility at the international level (Meyer and Leuschner 2015). One issue with the concept is, however, that both the number of sites in this network and the total area covered are very small. There are currently 115 sites with a total area of 430 ha included (Meyer and Leuschner 2015), corresponding to just 1 ha of arable land under conservation management to every 28,000 ha under regular arable management. This may not be sufficient to mitigate extinction risks for small and isolated populations, and to effectively boost overall arable biodiversity in the wider landscape. Additional re-introduction efforts as outlined below may therefore be required to ensure that extant populations of rare arable species are embedded in a dense network of populations. This would reduce the degree of isolation of individual populations, and facilitate gene flow and natural re-colonization processes which help counteract stochastic fluctuations leading to local extinction. Arable reserves may represent an important source of suitable local seed for such re-introduction efforts (e.g. Mayer, Weddige, and Wiesinger 2012), as do stocks preserved via ex-situ conservation.

VII. Ex-situ conservation

Plant species conservation can be divided into two different strategies: *in situ* and *ex situ* (Dulloo, Hunter, and Borelli 2010). **Ex-situ conservation** includes both the banking of seeds from *in situ* collections, and, particularly if required for renewing or enlarging the stock of seed, the propagation of 'founder collections' by cultivation in seed production beds. A disadvantage of *ex situ* seed propagation for conservation purposes is the operation of a more uniform selective pressure due to a lack of environmental variation that plants would experience *in situ*, e.g. due to different soil conditions, competition with other plant species, and adaptation to varying pollinator and herbivore communities. A good example for this type of risk is the study by Thomann et al. (2015). The authors collected seeds of *Cyanus segetum* in a region with increasing spring temperatures and a decline of pollinators during the last decades. Seeds sampled from one population in 1992 and 2010 were cultivated together in a common garden experiment. Plants of the descendant population (2010) flowered earlier and also produced larger flower heads with more peripheral florets than the plants of 1992. This example shows that even in a mere few decades a lack of pollination vectors may induce selection for traits relevant for the reproductive success of insect-pollinated plants. Under such conditions, environmental adaptation and fitness of *ex situ* propagated populations may be rapidly reduced compared to references *in situ*. Similarly, there are various risks during seed collection, cleaning, and storage stages that may result in reduced genetic diversity (Guerrant, Havens, and Maunder 2004; Basey, Fant, and Kramer 2015). Therefore, *ex-situ* conservation of non-crop arable plants via propagation cultures frequently results in a reduced genetic diversity and in the loss of alleles occurring in the wild (Brütting, Hensen, and Wesche 2013). On the other hand, considering the rapid decline of species diversity in agricultural landscapes, *ex situ* conservation is becoming increasingly important for protecting species from extinction (Gibson et al. 2006; Oesau and Kussel 2011; Brütting 2013). Therefore, already 15 members of the AG Erhaltungskulturen (2016) operate *ex situ* cultivation of arable plant species in Germany (mainly botanical gardens). Most of the

60 species cultivated there are particularly rare and threatened by extinction. However, to ensure that species overcome losses of genetic diversity, this propagation should be consequently accompanied by *in-situ* conservation and restoration measures covering a wide range of site and management conditions. In the following section, we provide an overview of how populations of rare arable plants can be successfully (re-)established by sowing.

VIII. Re-introduction of rare species

In various European countries, there have been efforts in recent years to re-establish threatened arable species, by harvesting seed from local remnant populations to be used for setting up new populations in regularly managed fields assumed to provide suitable habitat conditions for successful establishment and survival (Krick 2011; Cambecèdes, Largier, and Lombard 2012; Cornfield Flowers Project 2015; Lang et al. 2016a,b). Such targeted re-introduction of particular species has several advantages over an introduction via wildflower strips, as available in various European countries under existing AES (Haarland, Naisbit, and Bersier 2011; Dicks et al. 2013) to boost arable fauna. Unlike the latter, targeted re-establishment does not require spatial separation within the same field of conservation and crop-production objectives, and can thus be more easily incorporated into the operational processes of farming; at the same time, no further management effort may be required. Thus, such an approach should be relatively inexpensive, with the main expenses being seed sourcing and sowing. However, as there are few commercial sources for such seed, additional propagation may be required prior to re-introduction (see e.g. Cornfield Flowers Project 2015). In France, this requirement has led to the development of the "vraies messicoles" quality trademark to distinguish seeds of rare arable plants propagated from local source populations (Cambecèdes et al. 2015). Such sourcing of seed from within the same natural region, discussed above in the context of incorporating rare arable species into wildflower strip mixtures, is vital for ensuring adaptation to local conditions and for maintaining intraspecific genetic variation at larger spatial scales (Keller, Kollmann, and Edwards 2000). As most rare arable species are relatively uncompetitive, only limited effects to crop yields are to be expected, particularly when such species are sown at moderate densities (Lang et al. 2016b). Obviously, organically-farmed land, due to reduced N fertilization and a ban of herbicides, is likely much better suited for such introduction efforts than conventionally-farmed land (Mayer, Weddige, and Wiesinger 2012).

Table 1 provides an overview over the effects of various farming practices on establishment success of rare species, assessed via various parameters. The most suitable parameter for an assessment of whether introduced populations are likely to persist in the longer term may be total seed production, which may be conceived as a function of both plant establishment after introduction and of average individual seed production of successfully established plants reaching maturity, with the latter being linked to plant size. For adequate representation of the published literature on experimental introduction efforts, Table 1 contains information not only from studies reporting total seed production, but also from other studies, as long as these provide information on at least one aspect functionally related to total seed production. To provide the fullest possible overview, we also included studies based on seedling transplants (e.g. Kleijn and van der Vort 1997) and mesocosm studies (e.g. Epperlein et al. 2014).

As demonstrated by various studies listed in Table 1, sowing rare species without crops, or with crops sown at reduced densities, tends to boost rare species performance, mostly as a direct consequence of improved light availability to sown rare species (Kleijn and Van der Voort 1997). Differences in the performance of rare species in stands of different cereals (e.g. Svensson and Wigren 1982; Wilson 1994) may be similarly attributable to differences in light availability, depending on canopy structure and tillering capacity. Thus, spelt may be particularly compatible with rare species establishment, whereas rye may be much less so

(Lang et al. 2016a). However, as such characteristics can vary between different varieties of a given cereal, generalizations at crop species level must be operated carefully.

Due to the short-term nature of most experiments, and the limited numbers of crops covered by such studies, little is known about how more diverse crop rotations may affect the long-term persistence of rare plants once established. However, it appears likely that the more successful initial establishment and seed production are, the better the longer-term persistence of re-established populations.

Initial performance may be affected by several factors in addition to those already discussed. One such factor is initial sowing density of rare species. Comparing different sowing rates for *Legousia speculum-veneris*, *Consolida regalis* and *Buglossoides arvensis,* Lang et al. (2016b) found that establishment was unreliable when species were sown at rates lower than 25 seeds m^{-2}. On the other hand, sowing rates considerably above 100 seeds m^{-2} resulted in moderate but nonetheless significant yield losses when populations of target species developed well. Another factor is fertilizer application. In the presence of a crop, nitrogen fertilization tends to affect performance of re-introduced rare species mostly negatively (e.g. Wilson 1999; Kleijn and Van der Voort 1997). This is because crops have a superior ability to use added nutrients for rapid extra growth, and are thus able to exert greater competitive effects on sown rare species. However, in some instances, individuals of rare species characterized by relatively greater competitiveness may be able to compensate for reduced establishment by increased growth (Svensson and Wigren 1982; Kleijn and Van den Voort 1997). In contrast, in the absence of crops, introduced rare species generally benefit from additional fertilizer (Svensson and Wigren 1982; Kohler et al. 2011; Rotchés-Ribalta et al. 2016). However, some particularly uncompetitive rare species may fail to benefit from fertilizer even then, possibly due to being outcompeted by spontaneous non-crop species. One example for such an outcome may be *C. regalis* in Svensson and Wigren's (1982) study.

Herbicide application usually negatively affects establishment and vitality of rare arable plants (Wilson 1990). However, certain herbicide compounds are quite selective, and their use may even benefit establishment of rare species, as long as their sensitivity to a particular compound is low. One such example is provided by Pywell et al.'s (2010) study in which graminicide resulted in reduced competition from grasses, thus favoring sown rare broad-leaf species.

Timing of sowing also affects results. According to Jauzein (2011), a majority of rare arable species are winter annuals, and thus best suited to establish in autumn-sown crops with which their germination periodicity is synchronized, and in which no additional mortality occurs from cultivation in spring. In regions with cold winters and significant snow cover, sowing of winter annual species in early autumn tends to result in better establishment than late sowing (Lang et al. 2016a), whereas the opposite may apply in regions characterized by mild winters, such as much of the British Isles (Wilson 1990, 1994). However, a number of rare arable species, such as *Silene noctiflora*, *Glebionis segetum and Misopates orontium*, are spring-germinating and do not establish in autumn-sown crops (Wilson 1990, 1994). In fact, even a difference of just a few weeks can have a significant impact on rare species establishment (Wilson 1990, 1994).

Further research may be required on various aspects, some of which have not been covered by previous studies. One such aspect are the effects of forage crops. As outlined above, organic and low-intensity farming systems generally provide suitable conditions for successful establishment of rare species. In these farming systems, crops which maintain soil fertility, such as grass/clover mixes or legumes grown as forage crops, are an essential part of the rotation. However, due to their dense swards soon after initial establishment, and

their management by cutting and/or grazing, such crops may negatively affect establishment and seed-set of introduced rare plants. As previously suggested by Wilson (2000), these critical aspects should be targeted by future research, along with further studies providing information on seed bank persistence of rare arable species, which may enable these species to survive such unfavorable periods. Another aspect warranting further research is that only a limited range of species has so far been covered by re-introduction studies, with a bias towards the species typically found on calcareous or sandy substrates characterised by low levels of soil fertility. In contrast, with the exception of *Myosurus minimus*, species of seasonally-moist sites have so far been mostly ignored. Thus, future research must cover a much wider range of rare arable species, and redress the bias so far in terms of habitat preference.

Finally, some species, such as e.g. *Adonis spp.* or *Neslia paniculata*, frequently fail to establish at all (Schneider, Sukopp, and Sukopp 1994; Albrecht, Mayer, and Wiesinger 2009; Pywell et al. 2010; Mayer, Weddige, and Wiesinger 2012). Therefore, additional research may be required to more fully investigate the roles of dormancy characteristics and germination requirements in this failure, and, where applicable, to help develop suitable seed priming techniques and sowing strategies. Similar efforts are already underway for species from other habitats such as e.g. semi-natural grassland (Wagner et al. 2011).

IX. Conclusions

As shown in this review, contributions to the conservation of rare and threatened arable species can be made both by production-focused ('land sharing') farming systems tailored to take into account environmental considerations, as well as by ('land sparing') measures specifically aimed at species conservation. Regarding the former, organic farming and traditional low-intensity farming perform particularly well, whereas in integrated farming systems, weed control measures are usually applied according to economic thresholds, and preservation of rare arable plants could be undermined by the fact that these plants may predominantly occur in fields where such thresholds are exceeded (Albrecht 1989). Thus, any benefits of integrated farming to rare arable plants may be limited to situations where weed control measures are applied restrictively.

On conventionally-managed land, a different strategy is pursued in the form of specific conservation measures for rare arable plants targeted at field margins, such as conservation headlands (= 'field margin strips') or uncropped cultivated margins.

In fields with restricted weed control and fertilization, both uncropped cultivated margins and short (1-yr) fallow periods have proved particularly useful for arable plant conservation, as rare species get the opportunity to reproduce, and inversion tillage allows incorporation of seeds into the soil seed bank. On the other hand, long-term vegetation succession on uncultivated fallow / set-aside and the cultivation of cover crops tend to negatively affect populations of rare arable plants.

Another measure targeted at field margins, wildflower strips, are in their current form mostly aimed at the competing objective of providing resources for arable fauna. However, as suggested in this review, it may be possible to reconcile both objectives, e.g. if rare arable species were included in seed mixtures used to establish such strips, especially if seed material has been propagated from autochthonous sources. Additional research is required to investigate the various issues involved.

Particularly valuable sites, as e.g. identified by the German '100 Fields for Biodiversity' project or the British 'Important Arable Plant Areas' project, must be managed with a priority to preserve existing populations of rare plants. To this end, long-term commitment of land

owners must be secured, e.g. via long-term contractual agreements, or via awarding arable reserve status to some of these sites.

However, even taken together, the above measures may not be sufficient on their own to establish viable networks of populations of rare arable species in the wider landscape. To this end, additional targeted re-introduction of species may be required, using autochthonous seed material. As shown in this review, a considerable body of research regarding the compatibility of various farming practices with such re-introduction efforts already exists, but further research is required to close still-existing gaps in our knowledge.

We will not be able to turn back the clock in terms of agricultural management by returning to more traditional methods of farming on a large scale. However, using a well-integrated and coherent approach, combining all the tools available to us, it should be possible to achieve long-term preservation of these rare and threatened arable plants which are an important part of our cultural heritage.

X. Acknowledgements

XI. References

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Tab. 1: Overview of the effects of experimental management on parameters characterizing the performance of sown rare arable species, both in cropped and uncropped situations. To be included, a study had to report results for at least one of the following parameters: establishment, visual cover, seed production, biomass, or species richness. Results for biomass were included as they can be expected to correlate with seed production (e.g. shown for the level of plant individuals by Doll, Holm, and Søgaard 1995, Peters and Gerowitt 2014). For convenience, studies are listed according to farming practice, i.e. (1) crops sown at a single density vs. other crops or vs. no sowing, (2) variation in crop sowing density, (3) crop rotation, (4) fertilizer application and dose, (5) cutting of cover crop, (6) herbicide application, (7) timing of rare species sowing, and (8) discontinuation of cultivation in the second year after introduction. Unless otherwise stated, reported results refer to the first year after species introduction.

Farming practice	Source	Species	Parameter(s) assessed	Main findings	Comments
1. Crop sown					
Winter rye vs. winter spelt	Lang et al. (2015, 2016a)	*Buglossoides arvensis Consolida regalis Legousia speculum-veneris*	Establishment Total seed production	spelt > rye	
Winter rye with undersown cover crop (total cover almost 100%)	Albrecht, Mayer, and Wiesinger (2009)	*Buglossoides arvensis Consolida regalis Silene noctiflora*	Establishment	Low establishment in *C. regalis*, failure to establish in remaining species	
Winter wheat vs. grass vs. uncropped	Neve, Mortimer, and Putwain (1996)	*Agrostemma githago Bromus interruptus*	*A.githago* Establishment (Yr1) Total seed production (Yr1) Establishment (Yr2) *B. interruptus* Establishment (Yr1) Establishment (Yr2)	*A. githago* Establishment (Yr1): (Grass = uncropped) > wheat Seed production (Yr1): (Wheat = uncropped) > grass Establishment (Yr2): Wheat > uncropped > grass *B. interruptus* Establishment (Yr1): Grass = uncropped = wheat Establishment (Yr2): (Wheat = uncropped) > grass	Wheat establishment was very poor in year 1 (total mean cover: 8.1%)
Wheat vs. uncropped	Epperlein et al. (2014)	*Legousia speculum-veneris*	Standing biomass Total seed production	Aboveground biomass and seed production: uncropped > wheat	Indoor mesocosms; seedlings transplanted or manually thinned for fixed target density
Triticale vs. uncropped	Kohler et al. (2011)	*Agrostemma githago Ranunculus arvensis*	Total seed production	with fertilizer: triticale < uncropped without fertilizer: triticale = uncropped	Effect of crop treatment depends on fertilizer treatment (significant interaction!)
Wheat vs. uncropped	Hotze et al. (2009)	*Agrostemma githago Consolida regalis Cyanus segetum*	Visual cover	Uncropped > wheat	

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		Papaver rhoeas			
Wheat vs uncropped	Rotchés-Ribalta et al. (2016)	*Asperula arvensis* *Bifora testiculata* *Neslia paniculata* *Papaver argemone*	Individual biomass	For all species uncropped > wheat; effect tends to be more pronounced with fertilizer	Indoor mesocosms; seedlings sown in trays and manually transplanted into mesocosms; study also includes *S. pecten-veneris* which is considered rare in other parts of Europe
Winter wheat vs winter rye vs uncropped	Svensson and Wigren (1982)	*Agrostemma githago* *Bromus secalinus* *Buglossoides arvensis* *Cyanus segetum* *Consolida regalis* *Geranium dissectum* *Misopates orontium* *Papaver rhoeas*	Individual biomass	*B. secalinus, G. dissectum, M. orontium, R. arvensis*: uncropped > wheat > rye *C. segetum, C. regalis, P. rhoeas*: uncropped > (wheat = rye) *B. arvensis*: at high cereal sowing densities uncropped > wheat > rye; at low cereal sowing densities uncropped > (wheat = rye)	Both cereals sown at three densities (see also under 2 – Crop density); results visually interpreted on the basis of bar charts without error bars
Winter wheat vs. spring barley	Wilson, Boatman, and Edwards (1990), Wilson (1990)	*Alyssum alyssoides* *Arnoseris minima* *Buglossoides arvensis* *Bupleurum rotundifolium* *Filago pyramidata* *Glebionis segetum* *Misopates orontium* *Myosurus minimus* *Papaver argemone* *Ranunculus arvensis* *Silene noctiflora*	Establishment Total fruit production	*S. noctiflora, G. segetum, M. orontium, V. rimosa, M.orontium*: spring barley > winter wheat *P. argemone, A. alyssoides, F. pyramidata, M. minimus. B. arvensis, B. rotundifolium, R. arvensis, A. minima*: winter wheat > spring barley	Experiment carried out at two sites; sets of sown species differed slightly between sites
Winter wheat vs. winter barley	Wilson (1990, 1994)	*Adonis annua* *Agrostemma githago* *Buglossoides arvensis* *Papaver argemone* *Papaver hybridum* *Petroselinum segetum* *Ranunculus arvensis* *Scandix pecten-veneris* *Torilis arvensis* *Valerianella rimosa*	Establishment Total fruit production	*R. arvensis* and *B. arvensis*: wheat > barley *V. rimosa*: barley > wheat Other species: more indifferent or with opposite responses for each of two sites	Experiment carried out at two sites; sets of sown species differed slightly between sites
2. Crop density					
Crop thinning in winter rye: unthinned vs. 20, 40, 60, and 90% thinning	Kleijn and Van der Voort (1997)	*Cyanus segetum* *Glebionis segetum* *Hypochaeris glabra* *Misopates orontium*	Individual biomass	Low crop densities slightly better than normal ones	Seed sown in greenhouse and seedlings transplanted into field

		Papaver argemone			
Four densities each of winter wheat and winter rye: 0, 200, 400, and 600 seeds m^{-2}	Svensson and Wigren (1982)	*Agrostemma githago* *Bromus secalinus* *Buglossoides arvensis* *Cyanus segetum* *Consolida regalis* *Geranium dissectum* *Misopates orontium* *Papaver rhoeas*	Individual biomass	Uncropped generally best and lower cereal sowing densities generally better than higher densities	Results visually interpreted on the basis of bar charts without error bars; also including uncropped comparison (see also under 1 – Crop sown)
Five densities of winter wheat: ranging from 250-450 plants m^{-2}	Peters and Gerowitt (2014)	*Buglossoides arvensis* *Scandix pecten-veneris*	Individual seed production	*B. arvensis*: unaffected *S. pecten-veneris*: non-significant trend (P = 0.059) to produce more seeds at lower wheat densities	Preliminary experiment using outdoor mesocosms; Seed of rare species sown in greenhouse and seedlings transplanted into field
Two densities of winter wheat: 200 plants m-2 and 400 plants m2	Peters and Gerowitt (2014)	*Buglossoides arvensis* *Scandix pecten-veneris*	Individual seed production	Both species: higher seed production at the lower wheat density	Main experiment using outdoor mesocosms; Seed of rare species sown directly into mesocosms and manually thinned to target density
Three densities of winter rye: Uncropped vs ½ density vs standard density	Lang et al. (2016a)	*Buglossoides arvensis* *Consolida regalis* *Legousia speculum-veneris*	Establishment Total seed production	Plant number and seed production: uncropped > ½ density > standard density	also including uncropped comparison
Three densities of winter spelt: Uncropped vs 1/4 density vs standard density	Lang et al. (2015, 2016a)	*Buglossoides arvensis* *Consolida regalis* *Legousia speculum-veneris*	Establishment Total seed production	Plant number and seed production: uncropped > 1/4 density > standard density	
3.Crop rotation					
Four types of three-course rotation (organic)	Lang et al. (2015, 2016a)	*Buglossoides arvensis* *Consolida regalis* *Legousia speculum-veneris*	Establishment Total seed production	Inclusion of crops characterized by low total cover boosts both establishment and seed production; positive effect of uncropped or reduced-density spelt, negative effect of grass-clover	
Four-course rotation (organic): spelt – grass/clover – winter wheat – winter rye	Mayer, Weddige, and Wiesinger (2012)	*Allium vineale (bulbils)* *Buglossoides arvensis* *Consolida regalis* *Melampyrum arvense* *Neslia paniculata* *Phleum paniculatum*	Establishment (Yrs1-4)	Population decline in *M. arvense* and *C. regalis* in year 2 (=grass-clover), followed by a recovery from year 3 onwards	Failed establishment in *A. vineale, N. paniculata, V. dentata* and low establishment in *B. arvensis* and *P. paniculatum*

		Valerianella dentata			
4. Fertilization					
Nitrogen levels: 0, 75, 150 kg ha⁻¹	Wilson (1990, 1999)	*Alyssum alyssoides* *Arnoseris minima* *Bupleurum rotundifolium* *Buglossoides arvensis* *Glebionis segetum* *Filago pyramidata* *Misopates orontium* *Myosurus minimus* *Papaver argemone* *Papaver hybridum* *Ranunculus arvensis* *Scandix pecten-veneris* *Silene noctiflora* *Valerianella rimosa*	Establishment Total fruit production Individual inflorescence production	Establishment: *A. alyssoides, A. minima, F. pyramidata, M. orontium, M. minimus, P. argemone, P. hybridum, R. arvensis, S. pecten-veneris, V. rimosa*: negative nitrogen effect *S. noctiflora, B. rotundifolium, G. segetum, B. arvensis*: no significant nitrogen effect Fruit production*: A. alyssoides, A. minima, F. pyramidata, M. orontium, M. minimus*, P. hybridum: negative nitrogen effect *S. noctiflora, B. arvensis,, B. rotundifolium, G. segetum, P. argemone, S. pecten-veneris, R. arvensis, V. rimosa*: no significant nitrogen effect Inflorescence production: *A. alyssoides, B. arvensis, S, noctiflora, V. rimosa*: positive nitrogen effect Remaining species: no significant effect	Experiment carried out at two sites with winter wheat and spring barley, respectively; sets of sown species differed slightly between sites
Nitrogen levels: 0, 75, 150 kg ha⁻¹	Günter (1997)	*Bupleurum rotundifolium* *Cyanus segetum* *Consolida regalis* *Valerianella dentata*	Net seed production	*B. rotundifolium, C. segetum,* and *C. regalis* had significantly higher seed production with nitrogen, fertilization levels (75 vs. 150 kg N ha⁻¹) did not differ *V. dentata*: No significant effects	Seed mixture with winter wheat (400 seeds m⁻²)
NPK 20/6/6 200 kg ha⁻¹ vs 500 kg ha⁻¹	Svensson and Wigren (1982)	*Agrostemma githago* *Bromus secalinus* *Buglossoides arvensis* *Cyanus segetum* *Consolida regalis* *Geranium dissectum* *Misopates orontium* *Papaver rhoeas*	Individual biomass	*B. arvensis, P. rhoeas*: positive effect of high fertilizer level irrespective whether cereal has been sown or not *A. githago, G. dissectum. M. orontium*: positive effect of high fertilizer level without cereal sowing *C. regalis*: negative effect of high fertilizer level without cereal sowing	Results visually interpreted on the basis of bar charts without error bars; in some species, level of fertilizer application interacted with ceral sowing and with density of ceral sowing
25,000 kg sheep manure ha⁻¹	Kohler et al. (2011)	*Agrostemma githago* *Ranunculus arvensis*	Total seed production	*R. arvensis*: higher with fertilizer, but only when uncropped *A. githago*: higher with fertilizer, but effect more pronounced when uncropped	Effect of fertilizer treatment depends on crop treatment (significant interaction!)
2 nitrogen levels: 43.5 kg ha⁻¹ vs 87 kg ha⁻¹	Rotchés-Ribalta et al. (2016)	*Asperula arvensis* *Bifora testiculata* *Neslia paniculata* *Papaver argemone*	Individual biomass	For all species, higher N fertilizer level resulting in higher biomass; effect tends to be more pronounced in the absence of wheat	Indoor mesocosms; seedlings sown in trays and manually transplanted into mesocosms; study also includes *S. pecten-veneris* which is considered rare

					in other parts of Europe
2 nitrogen levels: 0 kg ha-1 vs 80-120 kg ha-1 (depending on crop)	Bischoff (1999)	*Buglossoides arvensis*	Individual seed production (Yrs1-3) Individual biomass (Yr3)	Seed production: higher with N fertilizer in years 1 (winter wheat) and 3 (spring barley), but not in year 2 (maize) Biomass: higher with N fertilizer	Seedlings transplanted into the field
Nitrogen levels: 0, 45, 90 kg ha^{-1}	Kleijn and Van der Voort (1997)	*Cyanus segetum Glebionis segetum Hypochaeris glabra Misopates orontium Papaver argemone*	Individual biomass	All species negatively affected by higher N fertilizer levels	Seed of rare species sown in greenhouse, seedlings transplanted into field
5. Cutting of cover crops in year 1					
Uncut vs cut 1 August vs cut 30 August	Neve, Mortimer, and Putwain (1996)	*Agrostemma githago Bromus interruptus*	Establishment (Yr2)	*A. githago*: (Uncut = late cut) > early cut *B. interruptus*: Late cut > early cut > uncut	
6.Herbicide application					
Effect of herbicides (atrazine, dicamba, glyphosate) on rare vs. common species	Egan, Graham, and Mortensen (2014)	*Asclepias tuberosa Bidens cernua Elymus hystrix Polygonum lapathifolia Verbena hastata*	Aboveground biomass Effective dose	Only few significant differences between rare species and common species (Point estimate for the effective dose in equal cases higher or lower for rare species relative to common species)	Bioassay experiment in the greenhouse Congeneric pairs with common species: *Asclepias syriaca, Bidens frondosa, Elymus riparius, Poygonum convolvulus, Vebena urticifolia*
Effect of herbicides (tribenuron and 2,4-D) on rare vs. common species	Rotchés-Ribalta et al. (2015b)	*Asperula arvensis Bupleurum rotundifolium Neslia paniculata Papaver argemone*	Total aboveground biomass, Total seed biomass Number of seeds	No significant link between rarity and herbicide sensitivity Sensitivity to tribenuron higher for *P. argemone* and *B. rotundifolium* than their paired common species, but lower for *A. arvensis* and *N. paniculata* compared to common species. .	Pairs with common species: *Scandix pecten-veneris, Rapistrum rugosum, Papaver rhoas, Galium aparine*
Mecoprop vs, Chlortholuron vs, MCPA vs, Ioxynil/bromoxyil vs. water	Wilson (1990)	*Buglossoides arvensis Glebionis segetum Misopates orotnium Papaver hybridum Ranunculus arvensis Scandix pecten-veneris Silene noctiflora*	Individual biomass Flower production	Chlortoluron and Ioxynil/bromoxyil: Significant reduction for all species Mecoprop: Significant reduction apart from *C. segetum* MCPA: No significant reduction	
Glyphosate vs. graminicide vs. unsprayed	Pywell et al. (2010)	*Adonis annua Agrostemma githago Cyanus segetum Glebionis segetum Papaver argemone*	Sown species richness per m^{-2}	Graminicide and unsprayed > glyphosate	Sown in mixture: Successful establishment in *A. githago, C. segetum, G. segetum, S. noctiflora*, poor establishment in *R. arvensis*, no establishment in

		Ranunculus arvensis *Silene noctiflora*			*A. annua* and *P. argemone*
Oxitril 4 vs. unsprayed	Svensson and Wigren (1982)	*Agrostemma githago* *Bromus secalinus* *Buglossoides arvensis* *Consolida regalis* *Cyanus segetum* *Geranium dissectum* *Misopates orontium* *Papaver rhoeas*	Individual biomass	Most species strongly negatively affected by oxitril 4, but *B. secalinus* only weakly affected, and in the latter species only when uncropped; in *B. arvensis*, herbicide effects more pronounced when cereal sown	Results visually interpreted on the basis of bar charts without error bars;
7.Timing of sowing					
Autumn (October) vs. winter (February)	Cambecèdes, Garcia, and Gire (2011)	*Agrostemma githago* *Bifora radians*	Establishment Seed production	Autumn > winter	
Autumn vs. spring	Pywell et al. (2010)	*Adonis annua* *Agrostemma githago* *Cyanus segetum* *Glebionis segetum* *Papaver argemone* *Ranunculus arvensis* *Silene noctiflora*	Visual cover	*A. githago, C. segetum*: autumn > spring *G. segetum, S. noctiflora*: no seasonal effect	Sown in mixture: Successful establishment in *A. githago, C. segetum, G. segetum, S. noctiflora*, poor establishment in *R. arvensis*, no establishment in *A. annua* and *P. argemone*
Three sowing dates each in winter wheat, winter barley, spring barley	Wilson (1990, 1994)	*Adonis annua* *Agrostemma githago* *Buglossoides arvensis* *Glebionis segetum* *Misopates orontium* *Papaver argemone* *Papaver hybridum* *Petroselinum segetum* *Ranunculus arvensis* *Scandix pecten-veneris* *Silene noctiflora* *Torilis arvensis* *Valerianella rimosa*	Establishment Total fruit production	Establishment: *A. annua, A. githago, B. arvensis, P. segetum, R. arvensis, S. pecten-veneris, T. arvensis,* : highest with autumn sowing *P. argemone, P. hybridum, V. rimosa*: highest with sowing from late autumn to spring *G. segetum, M. orontium, S. noctiflora*: highest with spring sowing Fruit production: patterns largely similar to establishment, but *V. rimosa* appears to have somewhat compensated for low establishment with early-autumn sowing by increased individual fruit production	Experiment carried out at two sites
Four sowing dates: early, mid and late autumn, early spring	Lang et al. (2016a), Prestele et al. (2013)	*Buglossoides arvensis* *Consolida regalis* *Legousia speculum-veneris*	Establishment Seed production	Early autumn > late autumn > spring	
8. Sowing density of rare species					
Ten levels in winter	Lang et al. (2016b)	*Buglossoides arvensis*	Establishment	< 25 seeds m^{-2}: establishment unreliable	

rye, ranging from 5 to 10.000 seeds m^{-2}		*Consolida regalis* *Legousia speculum-veneris*	Seed production	> 100 seeds m^{-2}: negative effects on crop yield	
Three sowing density in uncropped situation	Cambecèdes, Garcia, and Gire (2011)	*Agrostemma githago* *Anthemis altissima* *Bifora radians*	Establishment Seed production	Best seed productivity for highest density (respectively 100 – 50 – 250 seeds m^{-2})	
9. Waiving of cultivation					
2nd year: cultivation vs. no cultivation	Neve, Mortimer, and Putwain (1996)	*Agrostemma githago* *Bromus interruptus*		Waiving 2nd yr cultivation significantly declined *A. githago* and increased *B. interruptus* populations	