

Management options for the conservation of rare arable plants in Europe

H. Albrecht^a, J. Cambecèdes^{b,c}, M. Lang^a and M. Wagner^d

^aDepartment of Ecology, Restoration Ecology, Technische Universität München, Emil-Ramann-Strasse 6, Freising, Germany; ^bFédération des Conservatoires botaniques nationaux, Montreuil Cedex, France; ^cConservatoire botanique national des Pyrénées et de Midi-Pyrénées, Bagnères-de-Bigorre Cedex, France; ^dNERC Centre for Ecology & Hydrology, Benson Lane, Wallingford, Oxfordshire, UK

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.

ARTICLE HISTORY

Received 19 August 2016
Accepted 26 August 2016

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-crop 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 (Preston, Pearman, and Hall 2004; Willerding 1986). 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 Bökük 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 (Sissinagh 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 Tscharnkte 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 well-being. 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 twentieth 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 seeds (Kornaś 1988). Over the course of the twentieth 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 dependent on arable plant diversity, such as pollination and biological control (Landis, Wratten, and Gurr 2000; Marshall et al. 2003; Tscharnkte et al. 2005; Bianchi, Booij, and Tscharnkte 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. At present, 35% of plant species typically inhabiting arable fields are threatened in Germany (Korneck and Sukopp 1988), and 28% in England (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?

The nomenclature of plants follows version 1.1 of *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 that 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 above-ground 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. Before the widespread use of herbicides, early germination at low temperatures may have provided winter-annual species with a developmental advantage, as 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. Hence, 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 that disappeared from fields in the Languedoc (southern 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 that 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

Table 1. Overview of the effects of experimental management on parameters characterizing the performance of sown rare arable species, both in cropped and uncropped situations.

Farming practice	Source	Species	Parameter(s) assessed	Main findings	Comments
<i>1. Crop sown</i>					
Winter rye vs. winter spelt	Lang et al. (2015, 2016a)	<i>Buglossoides arvensis</i> <i>Consolida regalis</i> <i>Legousia speculum-veneris</i> <i>Buglossoides arvensis</i> <i>Consolida regalis</i> <i>Silene noctiflora</i>	Establishment Total seed production	spelt > rye	
Winter rye with undersown cover crop (total cover almost 100%)	Albrecht, Mayer, and Wiesinger (2009)	<i>Agrostemma githago</i> <i>Bromus interruptus</i>	Establishment Total seed production (Yr1) Establishment (Yr2) Total seed production (Yr1) Establishment (Yr2) Standing biomass Total seed production	Low establishment in <i>C. regalis</i> ; failure to establish in remaining species <i>A. githago</i> Establishment (Yr1): (Grass = uncropped) > wheat Seed production (Yr1): (Wheat = uncropped) > grass Establishment (Yr2): Wheat > uncropped > grass <i>B. interruptus</i> Establishment (Yr1): Grass = uncropped = wheat Establishment (Yr2): (Wheat = uncropped) > grass	Wheat establishment was very poor in year 1 (total mean cover: 8.1%)
Winter wheat vs. grass vs. uncropped	Neve, Mortimer, and Putwain (1996)				
Wheat vs. uncropped	Epperlein et al. (2014)	<i>Legousia speculum-veneris</i>	Establishment (Yr1) Establishment (Yr2) Standing biomass Total seed production	Above ground biomass and seed production: uncropped > wheat with fertilizer: triticale < uncropped without fertilizer: triticale = uncropped Uncropped > wheat	Indoor mesocosms; seedlings transplanted or manually thinned for fixed target density Effect of crop treatment depends on fertilizer treatment (significant interaction!)
Triticale vs. uncropped	Kohler et al. (2011)	<i>Agrostemma githago</i> <i>Ranunculus arvensis</i>	Visual cover		
Wheat vs. uncropped	Hotze et al. (2009)	<i>Agrostemma githago</i> <i>Consolida regalis</i> <i>Cyanus segetum</i> <i>Papaver rhoeas</i>	Individual biomass		
Wheat vs uncropped	Rotchés-Ribalta et al. (2016)	<i>Asperula arvensis</i> <i>Bifora testiculata</i> <i>Neslia paniculata</i> <i>Papaver argemone</i>	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 <i>Scandix pecten-veneris</i> , which is considered rare in other parts of Europe
Winter wheat vs winter rye vs uncropped	Svensson and Wigren (1982)	<i>Agrostemma githago</i> <i>Bromus secalinus</i> <i>Buglossoides arvensis</i> <i>Cyanus segetum</i> <i>Consolida regalis</i> <i>Geranium dissectum</i> <i>Misopates orontium</i> <i>Papaver rhoeas</i>	Individual biomass	<i>B. secalinus</i> , <i>G. dissectum</i> , <i>M. orontium</i> , <i>R. arvensis</i> ; uncropped > wheat > rye <i>C. segetum</i> , <i>C. regalis</i> , <i>P. rhoeas</i> ; uncropped > (wheat = rye) <i>B. arvensis</i> ; 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)	<i>Alyssum alyssoides</i> <i>Aroseris minima</i> <i>Buglossoides arvensis</i> <i>Bupleurum rotundifolium</i> <i>Filago pyramidata</i> <i>Glebionis segetum</i> <i>Misopates orontium</i> <i>Myosurus minimus</i> <i>Papaver argemone</i> <i>Ranunculus arvensis</i> <i>Silene noctiflora</i>	Establishment Total fruit production	<i>S. noctiflora</i> , <i>G. segetum</i> , <i>M. orontium</i> , <i>V. ramosa</i> , <i>M. orontium</i> : spring barley > winter wheat <i>P. argemone</i> , <i>A. alyssoides</i> , <i>F. pyramidata</i> , <i>M. minimus</i> , <i>B. arvensis</i> , <i>B. rotundifolium</i> , <i>R. arvensis</i> , <i>A. minima</i> : 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)	<i>Adonis annua</i> <i>Agrostemma githago</i> <i>Buglossoides arvensis</i> <i>Papaver argemone</i> <i>Papaver hybridum</i> <i>Petroselinum segetum</i> <i>Ranunculus arvensis</i> <i>Scandix pecten-veneris</i> <i>Torilis arvensis</i> <i>Valerianella rimosa</i>	Establishment Total fruit production	<i>R. arvensis</i> and <i>B. arvensis</i> : wheat > barley <i>V. rimosa</i> : 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)	<i>Cyanus segetum</i> <i>Glebionis segetum</i> <i>Hypochaeris glabra</i> <i>Misopates orontium</i> <i>Papaver argemone</i> <i>Agrostemma githago</i> <i>Bromus secalinus</i> <i>Buglossoides arvensis</i> <i>Cyanus segetum</i> <i>Consolida regalis</i> <i>Geranium dissectum</i> <i>Misopates orontium</i> <i>Papaver rhoeas</i>	Individual biomass	Low crop densities slightly better than normal ones	Seed sown in greenhouse and seedlings transplanted into field
Four densities each of winter wheat and winter rye: 0, 200, 400, and 600 seeds/m ²	Svensson and Wigren (1982)	<i>Papaver argemone</i> <i>Agrostemma githago</i> <i>Bromus secalinus</i> <i>Buglossoides arvensis</i> <i>Cyanus segetum</i> <i>Consolida regalis</i> <i>Geranium dissectum</i> <i>Misopates orontium</i> <i>Papaver rhoeas</i>	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)	<i>Buglossoides arvensis</i> <i>Scandix pecten-veneris</i>	Individual seed production	<i>B. arvensis</i> : unaffected <i>S. pecten-veneris</i> : non-significant trend ($p = 0.059$) to produce more seeds at lower wheat densities Both species: higher seed production at the lower wheat density	Preliminary experiment using outdoor mesocosms; Seed of rare species sown in greenhouse and seedlings transplanted into field Main experiment using outdoor mesocosms; Seed of rare species sown directly into mesocosms and manually thinned to target density also including uncropped comparison
Two densities of winter wheat: 200 plants/m ² and 400 plants/m ²	Peters and Gerowitt (2014)	<i>Buglossoides arvensis</i> <i>Scandix pecten-veneris</i>	Individual seed production	Plant number and seed production: uncropped > half density > standard density	
Three densities of winter rye: Uncropped vs half density vs standard density	Lang et al. (2016a)	<i>Buglossoides arvensis</i> <i>Consolida regalis</i> <i>Legousia speculum-veneris</i>	Establishment Total seed production	Plant number and seed production: uncropped > quarter density > standard density	
Three densities of winter spelt: Uncropped vs quarter density vs standard density	Lang et al. (2015, 2016a)	<i>Buglossoides arvensis</i> <i>Consolida regalis</i> <i>Legousia speculum-veneris</i>	Establishment Total seed production		
3. Crop rotation					
Four types of three-course rotation (organic)	Lang et al. (2015, 2016a)	<i>Buglossoides arvensis</i> <i>Consolida regalis</i> <i>Legousia speculum-veneris</i>	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)	<i>Allium vineale</i> (bulbils) <i>Buglossoides arvensis</i> <i>Consolida regalis</i> <i>Melampyrum arvense</i> <i>Neslia paniculata</i> <i>Phleum paniculatum</i> <i>Valerianella dentata</i>	Establishment (Yrs1–4)	Population decline in <i>M. arvense</i> and <i>C. regalis</i> in year 2 (=grass-clover), followed by a recovery from year 3 onwards	Failed establishment in <i>A. vineale</i> , <i>N. paniculata</i> , <i>V. dentata</i> and low establishment in <i>B. arvensis</i> and <i>P. paniculatum</i>

(Continued)

Table 1. (Continued).

Farming practice	Source	Species	Parameter(s) assessed	Main findings	Comments
4. Fertilization					
Nitrogen levels: 0, 75, 150 kg/ha	Wilson (1990, 1999)	<i>Alyssum alyssoides</i> <i>Artemisia minima</i> <i>Bupleurum rotundifolium</i> <i>Buglossoides arvensis</i> <i>Glebionis segetum</i> <i>Flago pyramidata</i> <i>Misopates orontium</i> <i>Myosurus minimus</i> <i>Papaver argemone</i> <i>Papaver hybridum</i> <i>Ranunculus arvensis</i> <i>Scandix pecten-veneris</i> <i>Silene noctiflora</i> <i>Valerianella rimosa</i>	Establishment Total fruit production Individual inflorescence production	Establishment: <i>A. alyssoides</i> , <i>A. minima</i> , <i>F. pyramidata</i> , <i>M. orontium</i> , <i>M. minimus</i> , <i>P. argemone</i> , <i>P. hybridum</i> , <i>R. arvensis</i> , <i>S. pecten-veneris</i> , <i>V. rimosa</i> : negative nitrogen effect <i>S. noctiflora</i> , <i>B. rotundifolium</i> , <i>G. segetum</i> , <i>B. arvensis</i> : no significant nitrogen effect Fruit production: <i>A. alyssoides</i> , <i>A. minima</i> , <i>F. pyramidata</i> , <i>M. orontium</i> , <i>M. minimus</i> , <i>P. hybridum</i> : negative nitrogen effect <i>S. noctiflora</i> , <i>B. arvensis</i> , <i>B. rotundifolium</i> , <i>G. segetum</i> , <i>P. argemone</i> , <i>S. pecten-veneris</i> , <i>R. arvensis</i> , <i>V. rimosa</i> : no significant nitrogen effect Inflorescence production: <i>A. alyssoides</i> , <i>B. arvensis</i> , <i>S. noctiflora</i> , <i>V. rimosa</i> : 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)	<i>Bupleurum rotundifolium</i> <i>Cyanus segetum</i> <i>Consolidida regalis</i> <i>Valerianella dentata</i>	Net seed production	<i>B. rotundifolium</i> , <i>C. segetum</i> , and <i>C. regalis</i> had significantly higher seed production with nitrogen, fertilization levels (75 vs. 150 kg N ha ⁻¹) did not differ <i>V. dentata</i> : No significant effects	Seed mixture with winter wheat (400 seeds m ⁻²)
NPK 20/6/6200 kg/ha vs 500 kg/ha	Svensson and Wigren (1982)	<i>Agrostemma githago</i> <i>Bromus secalinus</i> <i>Buglossoides arvensis</i> <i>Cyanus segetum</i> <i>Consolidida regalis</i> <i>Geranium dissectum</i> <i>Misopates orontium</i> <i>Papaver rhoeas</i>	Individual biomass	<i>B. arvensis</i> , <i>P. rhoeas</i> : positive effect of high fertilizer level irrespective whether cereal has been sown or not <i>A. githago</i> , <i>G. dissectum</i> , <i>M. orontium</i> : positive effect of high fertilizer level without cereal sowing <i>C. regalis</i> : 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 cereal sowing and with density of cereal sowing
25,000 kg sheep manure/ha	Kohler et al. (2011)	<i>Agrostemma githago</i> <i>Ranunculus arvensis</i>	Total seed production	<i>R. arvensis</i> : higher with fertilizer, but only when uncropped <i>A. githago</i> : 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 vs 87 kg/ha	Rotchés-Ribalta et al. (2016)	<i>Asperula arvensis</i> <i>Bifora testiculata</i> <i>Neslia paniculata</i> <i>Papaver argemone</i> <i>Buglossoides arvensis</i>	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 <i>S. pecten-veneris</i> which is considered rare in other parts of Europe
2 nitrogen levels: 0 kg/ha vs 80–120 kg/ha (depending on crop)	Bischoff (1999)		Individual seed production (Yrs1–3) Individual biomass (Yr3) Individual biomass	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	Kleijn and van der Voort (1997)	<i>Cyanus segetum</i> <i>Glebionis segetum</i> <i>Hypochaeris glabra</i> <i>Misopates orontium</i> <i>Papaver argemone</i>		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

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

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*, *Polygonum convolvulus*, *Verbena urticifolia*

Effect of herbicides (tribenuron and 24-D) on rare vs. common species

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.
Chlortholuron and loxynil/bromoxyl: Significant reduction for all species

Pairs with common species: *Scandix pecten-veneris*, *Rapistrum rugosum*, *Papaver rhoeas*, *Galium aparine*

Mecoprop vs Chlortholuron vs MCPA vs loxynil/bromoxyl vs. water

Mecoprop: Significant reduction apart from *C. segetum*
MCPA: No significant reduction

Glyphosate vs. graminicide vs. unsprayed

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 *A. annua* and *P. argemone*

Oxirtil 4 vs. unsprayed

Most species strongly negatively affected by oxirtil 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)

Autumn > winter

Autumn vs. spring

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*

(Continued)

Table 1. (Continued).

Farming practice	Source	Species	Parameter(s) assessed	Main findings	Comments
Three sowing dates each in winter wheat, winter barley, spring barley	Wilson (1990, 1994)	<i>Adonis annua</i> <i>Agrostemma githago</i> <i>Buglossoides arvensis</i> <i>Glebionis segetum</i> <i>Misopates orontium</i> <i>Papaver argemone</i> <i>Papaver hybridum</i> <i>Petroselinum segetum</i> <i>Ranunculus arvensis</i> <i>Scandix pecten-veneris</i> <i>Silene noctiflora</i> <i>Torilis arvensis</i> <i>Valerianella rimosa</i>	Establishment Total fruit production	Establishment: <i>A. annua</i> , <i>A. githago</i> , <i>B. arvensis</i> , <i>P. segetum</i> , <i>R. arvensis</i> , <i>S. pecten-veneris</i> , <i>T. arvensis</i> ; highest with autumn sowing <i>P. argemone</i> , <i>P. hybridum</i> , <i>V. rimosa</i> : highest with sowing from late autumn to spring <i>G. segetum</i> , <i>M. orontium</i> , <i>S. noctiflora</i> : highest with spring sowing Fruit production: patterns largely similar to establishment, but <i>V. rimosa</i> 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)	<i>Buglossoides arvensis</i> <i>Consolida regalis</i> <i>Legousia speculum-veneris</i>	Establishment Seed production	Early autumn > late autumn > spring	
8. Sowing density of rare species					
Ten levels in winter rye, ranging from 5 to 10,000 seeds/m ²	Lang et al. (2016b)	<i>Buglossoides arvensis</i> <i>Consolida regalis</i> <i>Legousia speculum-veneris</i>	Establishment Seed production	< 25 seeds/m ² : establishment unreliable > 100 seeds/m ² : negative effects on crop yield	
Three sowing density in uncropped situation	Cambedés, Garcia, and Gire (2011)	<i>Agrostemma githago</i> <i>Anthemis altissima</i> <i>Bifora radians</i>	Establishment Seed production	Best seed productivity for highest density (respectively 100–50–250 seeds/m ²)	
9. Discontinuation of cultivation					
2nd year: cultivation vs. no cultivation	Neve, Mortimer, and Putwain (1996)	<i>Agrostemma githago</i> <i>Bromus interruptus</i>		Waiving 2nd year cultivation significantly declined <i>A. githago</i> and increased <i>B. interruptus</i> populations	

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 Sosgaard 1995; Peters and Gerowitt 2014). For convenience, studies are listed according to farming practice, i.e. (1) crops sown at a single density versus other crops or versus 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, (8) sowing density of rare species, and (9) discontinuation of cultivation in the second year after introduction. Unless otherwise stated, reported results refer to the first year after species introduction.

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 der 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 that has affected rare arable plants from the beginning of the twentieth 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 the 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. Hence, *Camelina alyssum*, *Cuscuta epilinum*, *Lolium remotum*, *Lolium temulentum* and *Silene linicola*, which are all 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 that severely affected rare arable plants is the increased intensity and depth of soil tillage. This development particularly affected bulbous geophytes like *Gagea villosa*, *Gagea 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, Kollmann, and Albrecht 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 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 favourable habitats for rare arable plants (Stoate et al. 2001; Robinson and Sutherland 2002; Fried et al. 2009; Storkey et al. 2012; Rotchés-Ribalta et al. 2015c; Solé-Senan et al. 2014). Land abandonment and conversion to other forms of land use like forestry or grassland (Roche and Tatoni 2001; Stoate et al. 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 causes of the observed decline of rare arable plant species are the 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. Hence, to create conditions ensuring the long-term persistence of these traditional arable species, we have to develop tools that 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 realized in organic or in integrated farming systems.

Organic farming

Organic farming is characterized 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; Friebe and Köpke 1995; Becker and Hurler 1998; Hald 1999b; Kay and Gregory 1999; Rydberg and Milberg 2000; Hyvönen et al. 2003; Bengtsson, Ahnström, and Weibull 2005; Hole et al. 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 southeast of England, Kay and Gregory (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” 11 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. In contrast, no Biodiversity Action Plan 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 Friebe 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 that were 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 with 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* and *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. Hence, *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 to 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 therefore be limited to a minimum if management objectives for a given field include preservation of rare arable plants.

Integrated farming

Integrated farming aims to deliver sustainable agriculture with the careful use of resources (EISA (European Initiative for Sustainable Development in Agriculture) 2012). To this end, use of pesticides and fertilizers 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 nitrogen fertilizer; however, no rare species occurred. Similarly, in the TALISMAN study (Squire, Rodger, and Wright 2000), reduced application of nitrogen fertilizer and a 50% decrease of herbicide application resulted in markedly increased species richness in the soil seed bank after 5 years, but 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). Hence, results of the above-mentioned studies may nonetheless suggest that, compared with 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 5 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).

Low-intensity farming systems

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 that 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, Russo, and Benvenuti 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 (Fried et al. 2009; Gaba et al. 2010; 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 (Pal 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 hence 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 and Wilson 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. Hence, although 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 by Phalan et al. (2011) 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 to 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 with 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 fertilizer inputs in field margins signed up to the programme. Successful pilot studies led to more widespread adoption of these measures, and subsequently, the majority of German federal states introduced similar programmes. A peak was reached in the early 1990s, when a total area of more than 5000 ha was managed as *Ackerrandstreifen* (Wicke 1998). However, entry to these schemes was voluntary and unregulated, so 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 southwestern North Rhine-Westphalia (Friebe 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 summarized 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, among 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 that were managed so as 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 per cent of these margins supported populations of rare species, compared with only 15% of cereal crop controls. The most widespread rare arable species were *Euphorbia exigua*, *Legousia hybrida* and *Kickxia spuria*, each of which was found on 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 Biodiversity Action Plan 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. Although 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 (Haaland, 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 to 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, e.g. the “UFA Ackerflora” which comprises regionally sourced seeds of 32 arable species, most 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%, whereas 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, UK, 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. Among 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 was never 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 1- to 5-year old set-aside, but not on older set-aside. These results are in line with Dutoit et al. (2003) who found that resumption of cultivation after a 10-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 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 neighbouring 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 that had been sown to grass and clover 20 years previously, 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 before 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 to ensure local persistence during the fallow period.

European Community regulations also promoted set-aside measures that involved seeding a limited range of

cover crops as an alternative to leaving fields uncultivated. However, Waldhardt (1994) and Tschardt 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.

Although conservation measures targeted at field margins are 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 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, 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 Important Arable Plant Areas 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, and 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 agri-environment 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, 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 characterized 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 with reference plants *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 through 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 do not suffer 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, 2016b). Such targeted re-introduction of particular species has several advantages over an introduction through wildflower strips, as available in various European countries under existing AES (Haaland, 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, so can be more easily incorporated into the operational processes of farming; at the same time, no further management effort may be required. Hence, 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 before re-introduction (see for an example, the 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 nitrogen fertilization and a ban of herbicides, is likely to be much better suited for such introduction efforts than conventionally farmed land (Mayer, Weddige, and Wiesinger 2012).

Table 1 provides an overview of the effects of various farming practices on establishment success of rare species, assessed using 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 Voort 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. Hence, 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/m². On the other hand, sowing rates considerably above 100 seeds/m² 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. Kleijn and van der Voort 1997; Wilson 1999). This is because crops have a superior ability to use added nutrients for rapid extra growth, and so are 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 der 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 *Consolida 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 favouring 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 so 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 is the effect 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 that 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. Therefore, 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 unfavourable 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 characterized 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. 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 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). Hence, 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-year) 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, wild-flower 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 for example 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.

Acknowledgements

We thank Cath Shellswell from Plantlife for kindly answering our questions regarding Important Arable Plant Areas, and Eleanor Chandler for providing linguistic corrections. The authors would also like to thank the anonymous reviewers and the editor for making valuable comments and suggestions for improving this paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

H. Albrecht is researcher and lecturer at the Chair of Restoration Ecology of the Technical University of Munich, Germany. A major focus of his long term research activities is the ecology, management and conservation of arable plants. *Contribution:* He developed the concept of the review, wrote the draft version and coordinated the writing.

J. Cambecède is a conservation biologist working on rare plants conservation and habitat restauration at the Conservatoire botanique national des Pyrénées et de Midi-Pyrénées, France. *Contribution:* She provided the information about the situation of rare arable plants in France and current strategies for preservation and conservation.

M. Lang is a PhD student at the Technical University of Munich. Her doctoral thesis deals with the re-establishment of rare arable plants in agricultural landscapes. *Contribution:* She essentially contributed to the chapter on the re-introduction of rare arable plants and Table 1.

M. Wagner is a plant ecologist working at the NERC Centre for Ecology & Hydrology in Wallingford, UK. His research focuses on the management and restoration of semi-natural grassland and arable ecosystems, and on the roles of seed ecology and biotic interactions in such systems. *Contribution:* He improved the draft version by adding supplementary information, giving a detailed overview over the conservation of rare arable plants in UK and by editing the manuscript.

References

- AG Erhaltungskulturen. 2016. *Portal für Erhaltungskulturen einheimischer Wildpflanzen* [Online Portal for the Ex Situ Conservation of Native Plants]. URL. Accessed May 10, 2016. <http://www.ex-situ-erhaltung.de/>
- Albrecht, H. 1989. *Untersuchungen zur Veränderung der Segetalflora an sieben bayerischen Ackerstandorten zwischen den Erhebungszeiträumen 1951/68 und 1986/88* [Studies on the Change of the Segetal Flora in Seven Bavarian Arable Farming Regions Between the Survey Periods 1951/68 and 1986/88]. Dissertationes Botanicae 141. Stuttgart: Cramer / Borntraeger.
- Albrecht, H. 1995. “Changes in the Arable Weed Flora of Germany during the Last Five Decades.” In *Challenges for Weed Science in a Changing Europe*. Proceedings of the 9th EWRS-Symposium, Budapest, July 10-12 1995, 41-48.
- Albrecht, H. 2004. “Entwicklung der Diasporenbanken in Ackerböden sechs Jahre nach der Stilllegung [Development of the Diaspore Pool in Soil During Six Years Set Aside].” *Journal of Plant Diseases and Protection* Special Issue XIX: 49-56.
- Albrecht, H. 2005. “Development of Arable Weed Seedbanks during Six Years after the Change from Conventional to Organic Farming.” *Weed Research* 45: 339-350.
- Albrecht, H., and A. Mattheis. 1998. “The Effects of Organic and Integrated Farming on Rare Arable Weeds on the Forschungsverbund Agrarökosysteme München (Fam) Research Station in Southern Bavaria.” *Biological Conservation* 86: 347-356.
- Albrecht, H., and B. Sprenger. 2008. “Long Term Effects of Reduced Tillage on the Populations of Arable Weeds.” In *Perspectives for Agroecosystem Management. Balancing Environmental and Socioeconomic Demands*, edited by P. Schröder, J. Pfadenhauer, and J. C. Muench, 237-256. Amsterdam / Oxford: Elsevier.
- Albrecht, H., F. Mayer, and A. Mattheis. 2000. “*Veronica triphyllos* L.’ In The Tertiäreuhugelland landscape in southern Bavaria - an example for habitat isolation of a stenoeceous plant species in agroecosystems.” *Zeitschrift für Ökologie und Naturschutz* 8: 219-226.
- Albrecht, H., G. Anderlik-Wesinger, N. Kühn, A. Mattheis, and J. Pfadenhauer. 2008. “Effects of Land Use Changes on the Plant Species Diversity in Agricultural Ecosystems.” In *Perspectives for Agroecosystem Management. Balancing Environmental and Socioeconomic Demands*, edited by P. Schröder, J. Pfadenhauer, and J. C. Muench, 204-235. Amsterdam / Oxford: Elsevier.
- Albrecht, H., F. Mayer, and K. Wiesinger. 2009. “Biodiversität und Artenschutz bei Ackerwildpflanzen [Biodiversity and Species Conservation of Arable Weeds].” *Laufener Spezialbeiträge* 2009 (2): 135-142.
- Alfoeldi, T., A. Fliessbach, U. Geier, L. Kilcher, U. Niggli, L. Pfiffner, M. Stolze, and H. Willer. 2002. “Organic Agriculture and the Environment.” In *Organic Agriculture, Environment and Food Security*, edited by N. El-Hage

- Scialabba and C. Hattam, Environment and Natural Resources Series 4. Rome, Italy: Food and Agriculture Organisation of the United Nations (FAO). URL. Accessed May 10, 2016. http://www.fao.org/DOCREP/005/Y4137E/y4137e02.htm#P2_9
- Altenfelder, S., U. Raabe, and H. Albrecht. 2014. "Effects of Water Regime and Agricultural Land Use on Diversity and Species Composition of Vascular Plants Inhabiting Temporary Ponds in Northeastern Germany." *Tuexenia* 34: 145–162.
- Altenfelder, S., J. Kollmann, and H. Albrecht. 2016. "Effects of Farming Practice on Populations of Threatened Amphibious Plant Species in Temporarily Flooded Arable Fields: Implications for Conservation Management." *Agriculture, Ecosystems & Environment* 222: 30–37.
- Andreasen, C., H. Stryhn, and J. C. Streibig. 1996. "Decline in the Flora of Danish Arable Fields." *Journal of Applied Ecology* 33: 619–626.
- Armengot, L., L. José-María, J. M. Blanco-Moreno, A. Romero-Puente, and F. X. Sans. 2011. "Landscape and Land-Use Effects on Weed Flora in Mediterranean Cereal Fields." *Agriculture, Ecosystems and Environment* 142: 311–317.
- Auerswald, K., H. Albrecht, M. Kainz, and J. Pfadenhauer. 2000. "Principles of Sustainable Land-Use Systems Developed and Evaluated by the Munich Research Alliance on Agro-Ecosystems (FAM)." *Pethermanns Geographische Mitteilungen* 144 (2): 16–25.
- Austin, M. P., and B. O. Austin. 1980. "Behaviour of Experimental Plant Communities along a Nutrient Gradient." *Journal of Ecology* 68: 891–918.
- Barker, G. 2009. *The Agricultural Revolution in Prehistory: Why Did Foragers Become Farmers?* Oxford: Oxford University Press.
- Basey, A. C., J. B. Fant, and A. T. Kramer. 2015. "Producing Native Plant Materials for Restoration: 10 Rules to Collect and Maintain Genetic Diversity." *Native Plants Journal* 16: 37–53.
- Beaufoy, G., D. Baldock, and J. Clark. 1994. *The Nature of Farming: Low Intensity Farming Systems in Nine European Countries*. London: Institute for European Environmental Policy. URL. Accessed May 10, 2016. http://www.ieep.eu/assets/663/TheNatureOfFarming_1994_.pdf
- Becker, B., and K. Hurlé. 1998. "Unkrautflora auf Feldern mit unterschiedlich langer ökologischer Bewirtschaftung [Weed Flora in Fields with Varying Duration of Organic Farming]." *Journal of Plant Diseases and Protection* Special Issue XVI: 155–161.
- Bekker, R. M., J. P. Bakker, W. A. Ozinga, and K. Thompson. 2003. "Seed Traits: Essential for Understanding Seed Longevity." *Aspects of Applied Biology* 69: 1–9.
- Bengtsson, J., J. Ahnström, and A. C. Weibull. 2005. "The Effects of Organic Agriculture on Biodiversity and Abundance: A Meta-Analysis." *Journal of Applied Ecology* 42: 261–269.
- Bergmeier, E., and A. Strid. 2014. "Regional Diversity, Population Trends and Threat Assessment of the Weeds of Traditional Agriculture in Greece." *Botanical Journal of the Linnean Society* 175: 607–623.
- Berry, P., S. Ogilvy, and S. Gardner. 2005. *Integrated Farming and Biodiversity*. English Nature Research Reports 634. Peterborough, UK: English Nature.
- Bianchi, F., C. J. H. Booij, and T. Tschardt. 2006. "Sustainable Pest Regulation in Agricultural Landscapes: A Review on Landscape Composition, Biodiversity and Natural Pest Control." *Proceedings of the Royal Society B-Biological Sciences* 273: 1715–1727.
- Bischoff, A. 1999. "Zeitliche und räumliche Dynamik segetaler Populationen von *Lithospermum arvense* L. und ihre Beeinflussung durch Bewirtschaftungsfaktoren [Temporal and Spatial Dynamics of Segetal Populations of *Lithospermum arvense* L. and the Influence of Management Factors]." *Flora* 194: 127–136.
- Bischoff, A. 2005. "Analysis of Weed Dispersal to Predict Chances of Re-Colonisation." *Agriculture, Ecosystems and Environment* 106: 377–387.
- Boatman, N. D., H. R. Parry, J. D. Bishop, and A. G. S. Cuthbertson. 2007. "Impacts of Agricultural Change on Farmland Biodiversity in the UK." In *Biodiversity under Threat*, edited by R. E. Hester and R. M. Harrison, Issues in Environmental Science and Technology 25, 1–32. Cambridge UK: Royal Society of Chemistry.
- Boerlin, K. 2008. "Gesäte Segetalstreifen: Eine Möglichkeit zum Schutz der bedrohten Ackerbegleitflora? [Seeded Segetal Flower Strips: An Opportunity to Conserve the Threatened Arable Flora?]." Diploma Thesis, Zuerich School of Engineering (ZHAW).
- Bomanowska, A. 2010. "Threat to Arable Weeds in Poland in the Light of National and Regional Red Lists." *Plant Breeding and Seed Science* 61: 55–74.
- Bonneville, R., K. Saint-Hilaire, H. Brustel, J. Bugnicourt, J. Cambecèdes, S. Dejan, V. Sarthou, and F. Soldati. 2015. "Les jachères environnement et faune sauvage (JEFS): une opportunité pour la biodiversité de nos campagnes? [Wildlife-Friendly Management of Temporarily Uncultivated Fields: An Opportunity for the Biodiversity of our Rural Areas]." *Courrier de l'Environnement de l'INRA* 65: 95–110.
- Brütting, C. 2013. "Genetic Diversity and Population Structure of Arable Plants *in Situ* and *ex Situ* - How Sustainable is Long Term Cultivation in Botanical Gardens Compared to *in Situ* Conditions?" PhD diss., University Halle-Wittenberg, Germany.
- Brütting, C., S. Meyer, P. Kühne, I. Hensen, and K. Wesche. 2012. "Spatial Genetic Structure and Low Diversity of the Rare Arable Plant *Bupleurum rotundifolium* L. Indicate Fragmentation in Central Europe." *Agriculture, Ecosystems and Environment* 161: 70–77.
- Brütting, C., I. Hensen, and K. Wesche. 2013. "Ex situ Cultivation Affects Genetic Structure and Diversity in Arable Plants." *Plant Biology* 15: 505–513.
- Byfield, A. J., and P. J. Wilson. 2005. *Important Arable Plant Areas: Identifying Priority Sites for Arable Plant Conservation in the United Kingdom*. Salisbury, UK: Plantlife International.
- Callauch, R. 1981. "Ackerunkrautgesellschaften auf biologisch und konventionell bewirtschafteten Äckern in der weiteren Umgebung von Göttingen [Weed Communities in Organically and Conventionally Managed Fields in the Wider Surroundings of Göttingen]." *Tuexenia* 1: 25–38.
- Van Calster, H., R. Vandenberghe, M. Ruysen, K. Verheyen, M. Hermy, and G. Decocq. 2008. "Unexpected High 20th Century Floristic Losses in a Rural Landscape in Northern France." *Journal of Ecology* 96: 927–936.
- Cambecèdes, J., J. Garcia, and L. Gire. 2011. *Plan régional d'action pour la conservation des plantes messicoles et plantes remarquables des cultures, vignes et vergers en Midi-Pyrénées - 2e phase: mobilisation des acteurs et mise en place du réseau de conservation* [Regional Action Plan for the Conservation of Arable Plants and of Remarkable Plants of Crops, Vineyards and Orchards in the Midi-Pyrénées - 2nd Phase: Mobilization of Actors and Establishment of a Conservation Network]. Bagnères-de-Bigorre: Conservatoire Botanique National de Pyrénées et Midi-Pyrénées.

- Cambecèdes, J., G. Largier, and A. Lombard. 2012. *Plan national d'actions en faveur des plantes messicoles* [National Action Plan to Favour Typical Arable Plants]. Bagnères-De-Bigorre: Conservatoire Botanique National Des Pyrénées Et De Midi-Pyrénées - Fédération Des Conservatoires Botaniques Nationaux - Ministère De L'Écologie, Du Développement Durable Et De L'Énergie.
- Cambecèdes, J., S. Malaval, A. Bischoff, D. Provendier, M. Boutaud, J. Gourvil, G. Largier, and B. Dutréve. 2015. "Vraies Messicoles": A Label for Rare Arable Plants Produced from the Wild for Functional and Ornamental Purposes as a Way to Preserve Biodiversity." Montpellier: Proceedings 17th EWRS-Symposium: 245, Montpellier, 23-26 June 2015.
- Cannell, R. Q. 1985. "Reduced Tillage in North-West Europe - A Review." *Soil & Tillage Research* 5: 129-177.
- Chamorro, L., R. M. Masalles, and F. X. Sans. 2016. "Arable Weed Decline in Northeast Spain: Does Organic Farming Recover Functional Biodiversity?" *Agriculture Ecosystems and Environment* 223: 1-9.
- Chancellor, R. J. 1986. "Decline of Arable Weed Seeds during 20 Years in Soil under Grass and the Periodicity of Seedling Emergence after Cultivation." *Journal of Applied Ecology* 23: 631-637.
- Chancellor, R. J., J. D. Fryer, and G. W. Cussans. 1984. "The Effects of Agricultural Practices on Weeds in Arable Land." In *Agriculture and the Environment. Proceedings 13. ITE Symposium 28 February - 1 March 1984, Monks Wood Experimental Station, Institute of Terrestrial Ecology*, 89-94. Cambridge: Institute of Terrestrial Ecology.
- Cirujeda, A., J. Aibar, and C. Zaragoza. 2011. "Remarkable Changes of Weed Species in Spanish Cereal Fields from 1976 to 2007." *Agronomy for Sustainable Development* 31: 675-688.
- Clothier, L. 2013. "Campaign for the Farmed Environment: Entry Level Stewardship Option Uptake." *Defra Agricultural Change and Environment Observatory Research Report No. 32*.
- Cornfield Flowers Project. 2015. *Out of Intensive Care' 2010-2015 - A Report*. Hutton-Le-Hole, UK: Cornfield Flowers Project. Accessed May 10, 2016. <http://www.northyorkmoors.org.uk/looking-after/our-projects/cornfield-flowers-project/Cornfield-Flowers-Project-Out-of-Intensive-Care-Report.pdf>
- Cousens, R., and M. Mortimer. 1995. *Dynamics of Weed Populations*. Cambridge: Cambridge University Press.
- Critchley, C. N. R., J. A. Fowbert, and A. J. Sherwood. 2006. "The Effects of Annual Cultivation on Plant Community Composition of Uncropped Arable Field Boundary Strips." *Agriculture, Ecosystems and Environment* 113: 196-205.
- Dekker, J. 2011. *Evolutionary Ecology of Weeds and Invasive Plants. Weeds-R-us*. Accessed May 10, 2016. www.public.iastate.edu/~jdekker
- Diamond, J. 2002. "Evolution, Consequences and Future of Plant and Animal Domestication." *Nature* 418: 700-707.
- Dicks, L. V., J. E. Ashpole, J. Dänhardt, K. James, A. Jönsson, N. Randall, D. A. Showler, et al. 2013. "Farmland Conservation: Evidence for the Effects of Interventions in Northern and Western Europe." Exeter: Pelagic Publishing.
- Doll, H., U. Holm, and B. Sosgaard. 1995. "Effect of Crop Density on Competition by Wheat and Barley with *Agrostemma githago* and Other Weeds." *Weed Research* 35: 391-396.
- Dulloo, M. E., D. Hunter, and T. Borelli. 2010. "Ex situ and in situ Conservation of Agricultural Biodiversity: Major Advances and Research Needs." *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 38: 123-135.
- Dutoit, T., E. Gerbaud, E. Buisson, and P. Roche. 2003. "Dynamique d'une communauté d'adventices dans un champ de céréales créé après le labour d'une prairie semi-naturelle: rôles de la banque de graines permanente [Dynamics of a Spontaneous Plant Community in a Cereal Field which Developed after the Plowing Seminal Grassland: The Role of the Permanent Seed Bank]." *Ecoscience* 10: 225-235.
- Egan, J. F., I. M. Graham, and D. A. Mortensen. 2014. "A Comparison of the Herbicide Tolerances of Rare and Common Plants in an Agricultural Landscape." *Environmental Toxicology and Chemistry* 33: 696-702.
- Eggenschwiler, L., N. Richner, D. Schaffner, and K. Jacot. 2007. "Bedrohte Ackerbegleitflora: Wie fördern und erhalten? [How to Promote and Maintain the Endangered Arable Flora?]" *AGRARForschung* 14: 206-211.
- EISA (European Initiative for Sustainable Development in Agriculture). 2012. "European Integrated Farming Framework." URL. Accessed May 10, 2016. <http://sustainable-agriculture.org/integrated-farming/>
- Van Elsen, T. 1989. "Ackerwildkraut-Bestände biologisch-dynamisch und konventionell bewirtschafteter Hackfruchtäcker in der Niederrheinischen Bucht [Arable Plant Communities of Biodynamically and Conventionally Managed Root Crop Fields in the Lower Rhine Basin]." *Lebendige Erde* 4: 277-282.
- Van Elsen, T., and C. Hotze. 2008. "Die Integration autochthoner Ackerwildkräuter und der Kornrade in Blühstreifenmischungen für den ökologischen Landbau [Integration of Indigenous Arable Weeds and Corn Cockle in Flower Strip Mixtures for Organic Farming]." *Journal of Plant Diseases and Protection Special Issue XXI*: 373-378.
- El-Sheikh, M. A. 2013. "Weed Vegetation Ecology of Arable Land in Salalah, Southern Oman." *Saudi Journal of Biological Sciences* 20: 291-304.
- Epperlein, L. R. F., J. Prestele, H. Albrecht, and J. Kollmann. 2014. "Reintroduction of a Rare Arable Weed: Competition Effects on Weed Fitness and Crop Yield." *Agriculture, Ecosystems and Environment* 188: 57-62.
- Erviö, L. -R., and J. Salonen. 1987. "Changes in the Weed Population of Spring Cereals in Finland." *Annales Agriculturae Fenniae* 26: 201-226.
- European Council. 1992. "Regulation (EEC) 1765/92 of 30 June 1992 Establishing a Support System for Producers of Certain Arable Crops." *Official Journal of the European Communities L* 181: 12-20.
- Fischer, J., D. J. Abson, V. Butsic, M. J. Chappell, J. Ekroos, J. Hanspach, T. Kuemmerle, H. G. Smith, and H. von Wehrden. 2014. "Land Sparing versus Land Sharing: Moving Forward." *Conservation Letters* 7: 149-157.
- Franke, A. C., L. A. P. Lotz, W. J. Van Der Burg, and L. Van Overbeek. 2009. "The Role of Arable Weed Seeds for Agroecosystem Functioning." *Weed Research* 49: 131-141.
- Friebe, B. 1995. "Effizienz des Schutzprogrammes für Ackerwildkräuter [Efficiency of the Conservation Program for the Arable Weed Flora]." *Mitteilungen Der Landesanstalt für Ökologie, Landschaftsentwicklung und Forstplanung NRW* 4 (95): 14-19.
- Friebe, B., and U. Köpke. 1995. "Effects of Farming Systems on Biodiversity." In *Biodiversity and Land Use: The Role of Organic Farming*. Proceedings of the 1st ENOF Workshop: 11-21, Bonn, 8-9 December 1995. Barcelona: Multitext.
- Friebe, B., U. Prolingheuer, M. Wildung, and E. Meyerhoff. 2012. "Aufwertung der Agrarlandschaft durch ökologischen Landbau - Eine Möglichkeit der produktionsintegrierten Kompensation? (Teil 1) [Revaluation of Agricultural Landscape through Organic Farming - A Possibility

- of Production-Integrated Compensation (Part 1)]." *Naturschutz Und Landschaftsplanung* 44: 108–114.
- Fried, G., S. Petit, F. Dessaint, and X. Reboud. 2009. "Arable Weed Decline in Northern France: Crop Edges as Refugia for Weed Conservation?" *Biological Conservation* 142: 238–243.
- Fried, G., E. Kazakou, and S. Gaba. 2012. "Trajectories of Weed Communities Explained by Traits Associated with Species' Response to Management Practices." *Agriculture, Ecosystems and Environment* 158: 147–155.
- Gaba, S., B. Chauvel, F. Dessaint, V. Bretagnolle, and S. Petit. 2010. "Weed Species Richness in Winter Wheat Increases with Landscape Heterogeneity." *Agriculture, Ecosystems and Environment* 138: 318–323.
- Gabriel, D., and T. Tscharnkte. 2006. "Insect Pollinated Plants Benefit from Organic Farming." *Agriculture, Ecosystems and Environment* 118: 43–48.
- Gabriel, D., I. Roschewitz, T. Tscharnkte, and C. Thies. 2006. "Beta Diversity at Different Spatial Scales: Plant Communities in Organic and Conventional Agriculture." *Ecological Applications* 16: 2011–2021.
- Garibaldi, L. A., M. A. Aizen, A. M. Klein, S. A. Cunningham, and L. D. Harder. 2011. "Global Growth and Stability of Agricultural Yield Decrease with Pollinator Dependence." *Proceedings of the National Academy of Sciences of the United States of America* 108: 5909–5914.
- Gerowitt, B. 1992. "Dreijährige Versuche zur Anwendung eines Entscheidungsmodells für die Unkrautbekämpfung nach Schadensschwellen in Winterweizen [Three-Year Trials to Apply a Decision Model For Weed Control According to Economic Thresholds in Winter Wheat]." *Journal of Plant Diseases and Protection* Special Issue XIII: 301–310.
- Gibson, R. H., I. L. Nelson, G. W. Hopkins, B. J. Hamlett, and J. Memmott. 2006. "Pollinator Webs, Plant Communities and the Conservation of Rare Plants: Arable Weeds as a Case Study." *Journal of Applied Ecology* 43: 246–257.
- Gibson, R. H., S. Pearce, R. J. Morris, W. O. C. Symondson, and J. Memmott. 2007. "Plant Diversity and Land Use under Organic and Conventional Agriculture: A Whole-Farm Approach." *Journal of Applied Ecology* 44: 792–803.
- Grundy, A. C., A. Mead, and W. Bond. 1996. "Modelling the Effect of Weed-Seed Distribution in the Soil Profile on Seedling Emergence." *Weed Research* 36: 375–384.
- Guerrant, E. O., K. Havens, and M. Maunder. 2004. *Ex Situ Plant Conservation: Supporting Species Survival in the Wild*. Washington: Island Press.
- Günter, G. 1997. *Populationsbiologie seltener Segetalarten* [Population Biology of Rare Segetal Species]. Scripta Geobotanica 22. Göttingen: Goltze Verlag.
- Haaland, C., R. E. Naisbit, and L. -F. Bersier. 2011. "Sown Wildflower Strips for Insect Conservation: A Review." *Insect Conservation and Diversity* 4: 60–80.
- Hald, A. B. 1999a. "The Impact of Changing the Season in Which Cereals Are Sown on the Diversity of the Weed Flora in Rotational Fields in Denmark." *Journal of Applied Ecology* 36: 24–32.
- Hald, A. B. 1999b. "Weed Vegetation (Wild Flora) of Long Established Organic versus Conventional Cereal Fields in Denmark." *Annals of Applied Biology* 134: 307–314.
- Hawes, C., G. R. Squire, P. D. Hallett, C. A. Watson, and M. W. Young. 2010. "Arable Plant Communities as Indicators of Farming Practice." *Agriculture, Ecosystems and Environment* 138: 17–26.
- Hole, D. G., A. J. Perkins, J. D. Wilson, I. H. Alexander, P. V. Grice, and A. D. Evans. 2005. "Does Organic Farming Benefit Biodiversity?" *Biological Conservation* 122: 113–130.
- Hotze, C., and T. van Elsen. 2006. "Ackerwildkräuter konventionell und biologisch bewirtschafteter Äcker im östlichen Meißnervorland - Entwicklung in den letzten 30 Jahren [Arable Plants in Conventionally and Organically Managed Farmland in the Eastern Meißnervorland - Changes over the Last 30 Years]." *Journal of Plant Diseases and Protection* Special Issue XX: 547–555.
- Hotze, C., T. Van Elsen, T. Haase, J. Heß, and M. Otto. 2009. "Ackerwildkraut-Blühstreifen zur Integration autochthoner Ackerwildkräuter in ökologisch bewirtschaftete Ackerflächen [Arable Plant Strips to Integrate Autochthonous Arable Plants into Organic Arable Farming]." *Beiträge Zur 10. Wissenschaftstagung Ökologischer Landbau*. 426–429. 11–13 February 2009. Zurich. Berlin: Dr. Köster. URL. Accessed May 10, 2016. http://orgprints.org/14171/1/Hotze_14171.pdf
- Hulina, N. 2005. "List of Threatened Weeds in the Continental Part of Croatia and Their Possible Conservation." *Agriculturae Conspectus Scientificus* 70: 37–42.
- Hyvönen, T., and J. Salonen. 2002. "Weed Species Diversity and Community Composition in Cropping Practices at Two Intensity Levels - a Six-Year Experiment." *Plant Ecology* 159: 73–81.
- Hyvönen, T., E. Ketoja, J. Salonen, H. Jalli, and J. Tiainen. 2003. "Weed Species Diversity and Community Composition in Organic and Conventional Cropping of Spring Cereals." *Agriculture, Ecosystems and Environment* 97: 131–149.
- Jauzein, P. 2011. *Flore des champs cultivés* [The Flora of Cultivated Fields]. Versailles: Quae.
- Jones, N. E., and B. M. Smith. 2007. "Effects of Selective Herbicide Treatment, Row Width and Spring Cultivation on Weed and Arthropod Communities in Winter Wheat." *Aspects of Applied Biology* 81: 39–46.
- José-María, L., J. M. Blanco-Moreno, L. Armengot, and F. X. Sans. 2011. "How Does Agricultural Intensification Modulate Changes in Plant Community Composition?" *Agriculture, Ecosystems and Environment* 145: 77–84.
- Kay, S., and S. Gregory. 1999. *Rare Arable Flora Survey*. Little Wittenham: The Northmoor Trust.
- Keller, M., J. Kollmann, and P. J. Edwards. 2000. "Genetic Introgression from Distant Provenances Reduces Fitness in Local Weed Populations." *Journal of Applied Ecology* 37: 647–659.
- Kirmer, A., M. Pfau, S. Mann, M. Schrödter, and S. Tischew. 2016. "Erfolgreiche Anlage mehrjähriger Blühstreifen auf produktiven Standorten durch Ansaat wildkräuterreicher Samenmischungen und standortangepasste Pflege [Successful Establishment of Perennial Flower Strips on Productive Sites by Sowing Wildflower-Rich Seed Mixtures and Engaging in Site-Specific Management]." *Natur und Landschaft* 91: 109–118.
- Kleijn, D., and L. A. C. van der Voort. 1997. "Conservation Headlands for Rare Arable Weeds: The Effects of Fertilizer Application and Light Penetration on Plant Growth." *Biological Conservation* 81: 57–67.
- Kohler, F., C. Vandenberghe, R. Imstepf, and F. Gillet. 2011. "Restoration of Threatened Arable Weed Communities in Abandoned Mountainous Crop Fields." *Restoration Ecology* 19: 62–69.
- Kolářová, M., L. Tyšer, and J. Soukup. 2013a. "Diversity of Current Weed Vegetation on Arable Land in Selected Areas of the Czech Republic." *Plant, Soil and Environment* 59: 208–213.
- Kolářová, M., L. Tyšer, and J. Soukup. 2013b. "Impact of Site Conditions and Farming Practices on the Occurrence of Rare and Endangered Weeds on Arable Land in the Czech Republic." *Weed Research* 53: 489–498.

- Kornaś, J. 1988. "Speirochore Ackerwildkräuter: Von ökologischer Spezialisierung zum Aussterben [Speirochorous Arable Weeds: From Ecological Specialization to Extinction]." *Flora* 180: 83–91.
- Korneck, D., and H. Sukopp. 1988. *Rote Liste in der Bundesrepublik Deutschland ausgestorbenen, verschollenen und gefährdeten Farn- und Blütenpflanzen und ihre Auswertung für den Arten- und Biotopschutz* [Red List of Extinct, Lost, and Threatened Ferns and Flowering Plants of the Federal Republic of Germany and their Analysis for Species and Habitat Conservation]. Schriftenreihe Für Vegetationskunde 19. Bonn-Bad Godesberg: Bundesforschungsanstalt für Naturschutz und Landschaftsökologie.
- Krick, F. 2011. "Unkraut vergeht nicht - stimmt nicht! [Weeds Don't Vanish - That's Wrong!]." *LZ Rheinland* 32: 48–49.
- Kropáč, Z. 1988. "Veränderungen der Unkrautgemeinschaften in der Tschechoslowakei und die Konsequenzen für die landwirtschaftliche Praxis [Changes in Weed Communities in Czechoslovakia and The Consequences for the Agricultural Practice]." *Wissenschaftliche Zeitschrift der Universität Halle* 37: 100–126.
- Landis, D. A., S. D. Wratten, and G. M. Gurr. 2000. "Habitat Management to Conserve Natural Enemies of Arthropod Pests in Agriculture." *Annual Review of Entomology* 45: 175–201.
- Lang, M., C. Truffel, J. Prestele, K. Wiesinger, J. Kollmann, and H. Albrecht. 2015. "Einfluss von Deckfrucht und Fruchtfolge auf die Wiederansiedlung gefährdeter Ackerwildpflanzen [Effect of Cover Crop and Crop Rotation on The Re-Introduction of Endangered Arable Plants]." *Beiträge zur Wissenschaftstagung Ökologischer Landbau*. 231–235. 17–20 March 2015, Eberswalde, Germany. Berlin. Verlag Dr. Köster. URL. Accessed May 10, 2016. http://orgprints.org/27023/1/27023_lang.pdf
- Lang, M., H. Albrecht, S. Fink, A. Gärtner, C. Hotze, J. Kollmann, J. Prestele, T. van Elsen, and K. Wiesinger. 2016a. *Naturschutzleistungen des Ökologischen Landbaus: Wiederansiedlung seltener und gefährdeter Ackerwildpflanzen naturräumlicher Herkunft auf Ökobetrieben* [Conservation Benefits of Organic Farming: Re-Introduction of Rare and Endangered Arable Plants on Organic Farms]. Abschlussbericht BÖLN. Accessed May 10, 2016. www.orgprints.org/29843/
- Lang, M., J. Prestele, C. Fischer, J. Kollmann, and H. Albrecht. 2016b. "Re-Introduction of Rare Arable Plants by Seed Transfer. What Are the Optimal Sowing Rates?" *Ecology and Evolution* 6: 5506–5516.
- Law, E. A., and K. A. Wilson. 2015. "Providing Context for the Land-Sharing and Land-Sparing Debate." *Conservation Letters* 8: 404–413.
- Le Corre, V., S. Bellanger, J. -P. Guillemin, and H. Darmency. 2014. "Genetic Diversity of the Declining Arable Plant *Centaurea caryus*: Population Fragmentation within an Agricultural Landscape is Not Associated with Enhanced Spatial Genetic Structure." *Weed Research* 54: 536–544.
- Loddo, D., A. Russo, and S. Benvenuti. 2009. "Influence of Traditional Crop Seed Cleaning Techniques on the Presence of Cornflower (*Centaurea cyanus* L.) and Corn Cockle (*Agrostemma githago* L.) in Winter Cereal Fields." In *Weeds and Biodiversity*. 3rd workshop of the EWRS Working Group Weeds and Biodiversity: 45, Lleida (Spain), 12–13 March 2009. URL. Accessed May 10, 2016. http://www.ewrs.org/biodiversity/doc/EWRS_Biodiversity_Lleida_Proceedings_2009.pdf
- Lososová, Z. 2003. "Estimating past Distribution of Vanishing Weed Vegetation in South Moravia." *Preslia* 75: 71–79.
- Magri, D. 2008. "Patterns of Post-Glacial Spread and the Extent of Glacial Refugia of European Beech (*Fagus sylvatica*)." *Journal of Biogeography* 35: 450–463.
- Maillet, J., and M. Godron. 1997. "Caractéristiques bionomiques des messicoles et incidence sur leurs capacités de maintien dans les agrosystèmes [Ecological Characteristics of Typical Arable Plants and the Impact on their Capacity to Survive in Agroecosystems]." In *Faut-il sauver les mauvaises herbes? Colloquium at Conservatoire Botanique National de Gap-Charance*, 105–124, Gap, France, June 9–12, 1993.
- Májeková, J., M. Zaliberova, J. Šibík, and K. Klimova. 2010. "Changes in Segetal Vegetation in the Borska Nižina Lowland (Slovakia) over 50 Years." *Biologia* 65: 465–478.
- Marshall, E. J. P. 1989. "Distribution Patterns of Plants Associated with Arable Field Edges." *Journal of Applied Ecology* 26: 247–257.
- Marshall, E. J. P., V. K. Brown, N. D. Boatman, P. J. W. Lutman, G. R. Squire, and L. K. Ward. 2003. "The Role of Weeds in Supporting Biological Diversity within Fields." *Weed Research* 43: 77–89.
- Mattheis, A., and A. Otte. 1994. "Ergebnisse der Erfolgskontrollen zum Ackerrandstreifenprogramm im Regierungsbezirk Oberbayern 1985–1991 [Results of the Assessment of the Field Margins Program in the District of Upper Bavaria 1985–1991]." *Schriftenreihe der Stiftung zum Schutz gefährdeter Pflanzen* 5: 56–71.
- Mayer, F., and H. Albrecht. 2008. "Dispersal Strategies: Responsible for Species Success in Arable Ecosystems?" In *Perspectives for Agroecosystem Management. Balancing Environmental and Socioeconomic Demands*, edited by P. Schröder, J. Pfadenhauer, and J. C. Muench, 257–278. Amsterdam / Oxford: Elsevier.
- Mayer, F., A. Weddige, and K. Wiesinger. 2012. "Ansiedlung seltener Ackerwildkräuter auf einem Öko-Betrieb des südlichen Frankenjura [Establishment of Rare Arable Plants on an Organic Farm in Southern Frankenjura]." *Schriftenreihe der LfL* 4: 128–132.
- Meyer, S., and C. Leuschner. 2015. *100 Äcker für die Vielfalt - Initiativen zur Förderung der Ackerwildkrautflora in Deutschland* [100 Fields for Biodiversity - Initiatives to Promote the Arable Weed Flora in Germany]. Göttingen: Universitätsverlag.
- Meyer, S., K. Wesche, B. Krause, and C. Leuschner. 2013a. "Dramatic Losses of Specialist Arable Plants in Central Germany since the 1950s/60s - a Cross-Regional Analysis." *Diversity and Distributions* 19: 1175–1187.
- Meyer, S., W. Hilbig, K. Steffen, and S. Schuch. 2013b. "Ackerwildkrautschutz - Eine Bibliographie [Arable Plant Conservation - A Bibliography]." *BfN-Skripten* 351.url. Accessed May 10, 2016. <https://www.bfn.de/fileadmin/BfN/service/Dokumente/skripten/skript403.pdf>
- Moreby, S. J., N. J. Aebischer, S. E. Southway, and N. W. Sotherton. 1994. "A Comparison of the Flora and the Arthropod Fauna of Organically and Conventionally Grown Winter Wheat in Southern England." *Annals of Applied Biology* 125: 13–27.
- Moreira, I., T. Vasconcelos, A. Monteiro, and E. Sousa. 1996. "Salvem-se ervas daninhas messicolas [Save The Segetal Weed Flora]." 2F: 1–4. 2nd Congresso Nacional de Economistas Agrícolas, Evora.
- Morris, N. L., P. C. H. Miller, J. H. J. H. Orson, and R. J. Froud-Williams. 2010. "The Adoption of Non-Inversion Tillage Systems in the United Kingdom and the Agronomic Impact on Soil, Crops and the Environment—A Review." *Soil & Tillage Research* 108: 1–15.

- Moyse, R. I. 2013. "Response of Broad-Leaved Cudweed *Filago pyramidata* to Cultivation under Environmental Stewardship at Ranscombe Farm Reserve, Kent, UK." *Conservation Evidence* 10: 72–76.
- Moyse, R. I., and C. Shellswell. 2016. "A Comparison between the Impacts of Ploughing and Minimum Tillage on Arable Plant Assemblages at Ranscombe Farm Reserve, Kent, UK." *Conservation Evidence* 13: 33–37.
- Nentwig, W., T. Frank, and C. Lethmayer. 1998. "Sown Weed Strips: Artificial Ecological Compensation Areas as an Important Tool in Conservation Biological Control." In *Conservation Biological Control*, edited by P. Barbosa, 133–153. San Diego: Academic Press.
- Neve, P., A. M. Mortimer, and P. D. Putwain. 1996. "Management Options for the Establishment of Communities of Rare Arable Weeds on Set-aside Land." *Aspects of Applied Biology* 44: 257–262.
- Nowak, A., S. Nowak, M. Nobis, and A. Nobis. 2014. "A Report on the Conservation Status of Segetal Weeds in Tajikistan." *Weed Research* 54: 635–648.
- Oesau, A., and E. Jörg. 1994. "The Pilot-Project: 'Field Margin Strips' in Rheinland-Pfalz (1984–1993)." In *Field Margin Strip Programmes. Proceedings of a Technical Seminar on Filed Margin-Strip Programmes of the Landesanstalt für Pflanzenbau und Pflanzenschutz Rheinland-Pfalz*, 29–34, Mainz, Germany, May 25–27, 1994.
- Oesau, A., and N. Kussel. 2011. "Jahre Erhaltungskulturen Ackerwildkräuter in Rheinland-Pfalz [10 Years of in Situ Conservation of Arable Plants in Rheinland-Pfalz]." *Fauna Flora Rheinland-Pfalz* 12: 223–240.
- Osbornová, J., M. Kovářová, J. Lepš, and K. Prach. 1990. "Succession in Abandoned Fields. Studies in Central Bohemia, Czechoslovakia." *Geobotany* 15.
- Otte, A., S. Bissels, and R. Waldhardt. 2006. "Samen-, Keimungs-, und Habitateigenschaften: Welche Parameter erklären Veränderungstendenzen in der Häufigkeit von Ackerwildkräutern in Deutschland? [Seed, Germination, and Site Characteristics: Which Parameters of Arable Weeds do Explain the Change of Frequency in Germany?]" *Journal of Plant Diseases and Protection* Special Issue XX: 507–516.
- Pal, R., G. Pinke, Z. Botta-Dukát, G. Campetella, S. Bartha, R. Kalocsai, and A. Lengyel. 2013. "Can Management Intensity Be More Important than Environmental Factors? A Case Study along an Extreme Elevation Gradient from Central Italian Cereal Fields." *Plant Biosystems* 147: 343–353.
- Parish, D. M. B., C. Hawes, S. P. Hoad, P. P. M. Iannetta, and G. R. Squire. 2009. "The Contribution of Arable Weeds to Biodiversity." In *Weeds: Management, Economic Impacts and Biology*, edited by R. V. Kingely, 61–76. Hauppauge, NY, USA: Nova Science.
- Peters, K., and B. Gerowitt. 2014. "Response of the Two Rare Arable Weed Species *Lithospermum arvense* and *Scandix pecten-veneris* to Climate Change Conditions." *Plant Ecology* 215: 1013–1023.
- Phalan, B., M. Onial, A. Balmford, and R. E. Green. 2011. "Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared." *Science* 333: 1289–1291.
- Pinke, G., and R. M. Gunton. 2014. "Refining Rare Weed Trait Syndromes along Arable Intensification Gradients." *Journal of Vegetation Science* 25: 879–989.
- Pinke, G., and R. Pál. 2009. "Floristic Composition and Conservation Value of the Stubble-Field Weed Community, Dominated by *Stachys annua* in Western Hungary." *Biologia* 64: 279–291.
- Pinke, G., R. Pál, Z. Botta-Dukát, and M. Chytrý. 2009. "Weed Vegetation and Its Conservation Value in Three Management Systems of Hungarian Winter Cereals on Base-Rich Soils." *Weed Research* 49: 544–551.
- Pinke, G., G. Király, Z. Barina, A. Mesterházy, L. Balogh, J. Csiky, A. Schmotzer, A. V. Molnár, and R. W. Pál. 2011. "Assessment of Endangered Synanthropic Plants of Hungary with Special Attention to Arable Weeds." *Plant Biosystems* 145: 426–435.
- Plakolm, G. 1989. "Unkrautuntersuchungen in biologisch und konventionell bewirtschafteten Getreideäckern Oberösterreichs [Weed Investigations in Organically and Conventionally Managed Cereal Fields in Upper Austria]." PhD diss., University of Soil Sciences, Vienna.
- Pointereau, P., F. Coulon, and J. André. 2010. "Analyse des pratiques agricoles favorables aux plantes messicoles [Analysis of Management Practices which Benefit Typical Arable Plants]." Conservatoire Botanique des Pyrénées et de Midi-Pyrénées. URL. Accessed May 10, 2016. <http://www.ecodiag.eu/ftp/MP2010250512.pdf>
- Potts, G. R., J. A. Ewald, and N. J. Aebischer. 2010. "Long-Term Changes in the Flora of the Cereal Ecosystem on the Sussex Downs, England, Focusing on the Years 1968–2005." *Journal of Applied Ecology* 47: 215–226.
- Prestele, J., J. Kollmann, H. Albrecht, and K. Wiesinger. 2013. "Wiederansiedlung seltener und gefährdeter Ackerwildpflanzen auf Ökobetrieben. Teilprojekt Freising: Einfluss der Feldfrucht und Aussaatzeitpunkt [Re-Introduction of Rare and Endangered Arable Weeds on Organic Farms. Project Freising: Influence of Crop Type and Sowing Date]." *Beitrag Zur 12. Wissenschaftstagung Ökologischer Landbau*, 390–393. 5–8 March 2013. Berlin: Dr. Köster. Accessed May 2016 http://orgprints.org/21519/1/21519_Presteale.pdf
- Preston, C. D., D. A. Pearman, and A. R. Hall. 2004. "Archaeophytes in Britain." *Botanical Journal of the Linnean Society* 145: 257–294.
- Pywell, R. F., L. Hulmes, W. R. Meek, and M. Nowakowski. 2010. "Practical Management of Scarce Arable Plant Populations. in: Agri-Environment Schemes - What Have They Achieved and Where Do We Go from Here?" *Aspects of Applied Biology* 100: 175–182.
- Raabe, U. 2009. "*Chara baueri* Rediscovered in Germany - plus Additional Notes on Gustav Heinrich Bauer (1794–1888) and His Herbarium." *ICGC News* 20: 13–16.
- Randall, N. P., and K. L. James. 2012. "The Effectiveness of Integrated Farm Management, Organic Farming and Agri-Environment Schemes for Conserving Biodiversity in Temperate Europe - a Systematic Map." *Environmental Evidence* 1.
- Richner, N., R. Holderegger, H. P. Linder, and T. Walter. 2015. "Reviewing Change in the Arable Flora of Europe: A Meta-Analysis." *Weed Research* 55: 1–13.
- Ries, C. 1992. *Überblick über die Ackerunkrautvegetation Österreichs und ihre Entwicklung in neuerer Zeit* [Overview of the Weed Vegetation of Austria and its Development in the Recent Past]. Dissertationes Botanicae 187. Stuttgart: Cramer/Borntraeger.
- Robinson, R. A., and W. J. Sutherland. 2002. "Post-War Changes in Arable Farming and Biodiversity in Great Britain." *Journal of Applied Ecology* 39: 157–176.
- Roche, P., and T. Tatoni. 2001. *Suivi scientifique de l'opération locale agriculture-environnement: protection in situ des agrosystèmes à messicoles* [Scientific Monitoring of Local Agri-Environmental Measures: In Situ Protection of Habitats of Typical Arable Plants]. Rapport final

- 1997–2001 - PNR du Lubéron, Université D' Aix Marseille III.
- Rollin, O., G. Benelli, S. Benvenuti, A. Decourtye, S. D. Wratten, A. Canale, and N. Desneux. 2016. "Weed-Insect Pollinator Networks as Bio-Indicators of Ecological Sustainability in Agriculture. a Review." *Agronomy for Sustainable Development* 36: 8.
- Romero, A., L. Chamorro, and F. X. Sans. 2008. "Weed Diversity in Crop Edges and Inner Fields of Organic and Conventional Dryland Winter Cereal Crops in NE Spain." *Agriculture, Ecosystems and Environment* 124: 97–104.
- Rotchés-Ribalta, R., J. M. Blanco-Moreno, L. Armengot, L. José-María, and F. X. Sans. 2015a. "Which Conditions Determine the Presence of Rare Weeds in Arable Fields?" *Agriculture, Ecosystems and Environment* 203: 55–61.
- Rotchés-Ribalta, R., C. Boutin, J. M. Blanco-Moreno, D. Carpenter, and F. X. Sans. 2015b. "Herbicide Impact on the Growth and Reproduction of Characteristic and Rare Arable Weeds of Winter Cereal Fields." *Ecotoxicology* 24: 991–1003.
- Rotchés-Ribalta, R., J. M. Blanco-Moreno, L. Armengot, L. Chamorro, F. X. Sans, and M. Hermy. 2015c. "Both Farming Practices and Landscape Characteristics Determine the Diversity of Characteristic and Rare Arable Weeds in Organically Managed Fields." *Applied Vegetation Science* 18: 423–431.
- Rotchés-Ribalta, R., J. M. Blanco-Moreno, L. Armengot, and F. X. Sans. 2016. "Responses of Rare and Common Segetal Species to Wheat Competition and Fertiliser Type and Doses." *Weed Research* 56: 114–123.
- Rühl, A. T., R. L. Eckstein, A. Otte, and T. W. Donath. 2016. "Distinct Germination Response of Endangered and Common Arable Weeds to Reduced Water Potential." *Plant Biology* 18: 83–90.
- Rydberg, N. T., and P. Milberg. 2000. "A Survey of Weeds in Organic Farming in Sweden." *Biological Agriculture and Horticulture* 18: 175–185.
- Saatkamp, A., L. Affre, T. Dutoit, and P. Poschlo. 2011. "Germination Traits Explain Soil Seed Persistence across Species: The Case of Mediterranean Annual Plants in Cereal Fields." *Annals of Botany* 107: 415–426.
- Salisbury, E. 1961. *Weeds & Aliens*. London: Collins.
- Schacherer, A. 1994. "Das niedersächsische Ackerwildkrautprogramm - Ergebnisse des Pilotprojektes [Lower Saxony's Arable Weed Program - Results of the Pilot Project]." *Schriftenreihe der Stiftung zum Schutz gefährdeter Pflanzen* 5: 2–77.
- Schellhorn, N. A., and V. L. Sork. 1997. "The Impact of Weed Diversity on Insect Populations Dynamics and Crop Yield in Collards, *Brassica oleracea* (Brassicaceae)." *Oecologia* 111: 233–240.
- Schneider, L. 2014. "Erhaltung einer wertvollen Ackerbegleitflora [Conservation of a Valuable Arable Field Flora]." *Umwelt Aargau* 66: 59–62.
- Schneider, C., U. Sukopp, and H. Sukopp. 1994. *Biologisch-ökologische Grundlagen Des Schutzes Gefährdeter Segetalpflanzen*. [Biological and Ecological Basics for the Conservation of Threatened Segetal Plants]. Schriftenreihe Für Vegetationskunde 26. Bonn-Bad Godesberg: Bundesamt für Naturschutz.
- Schumacher, W. 1980. "Schutz und Erhaltung gefährdeter Ackerwildkräuter durch Integration von landwirtschaftlicher Nutzung und Naturschutz [Protection and Conservation of Endangered Arable Weeds through Integration of Agricultural Land Use and Nature Conservation]." *Natur und Landschaft* 55: 447–453.
- Sissingh, G. 1950. *Onkruid-associaties in Nederland. Een sociologisch-systeematische beschrijvink van de klasse Rudereto-Secalinetea Br.-Bl.* 1936 [Weed Associations of the Netherlands: A Phytosociological Description of the Rudereto-Secalinetea Br.-Bl. 1936 class]. Gravenhage: Verslagen van Landbouwkundig Onderzoek 56.15.
- Skrajna, T., H. Kubicka, and Z. Rzymowska. 2012. "*Illecebrum verticillatum* L. - Endangered Species in Agroecosystems of Eastern Poland: Assessment of Ecological and Genetic Indicators for Protection Goals." *Polish Journal of Ecology* 60: 577–589.
- Smallshire, D., and A. I. Cooke. 1999. "Field Margins in UK Agri-Environment Schemes." *Aspects of Applied Biology* 54: 19–28.
- Solé-Senan, X. O., A. Juárez-Escario, J. Antoni Conesa, J. Torra, A. Royo-Esnal, and J. Recasens. 2014. "Plant Diversity in Mediterranean Cereal Fields: Unraveling the Effect of Landscape Complexity on Rare Arable Plants." *Agriculture Ecosystems and Environment* 185: 221–230.
- Sparrius, L., B. Odé, and R. Beringen. 2012. "Rode Lijst Vaatplanten 2012 volgens Nederlandse en IUCN-criteria [Red List of Vascular Plants 2012 according to Dutch and IUCN Criteria]." FLORON Rapport 57. Nijmegen: FLORON.
- Squire, G. R., S. Rodger, and G. Wright. 2000. "Community-Scale Seedbank Response to Less Intense Rotation and Reduced Herbicide Input." *Annals of Applied Biology* 136: 47–57.
- Still, K., and A. Byfield. 2007. *New Priorities for Arable Plant Conservation*. Salisbury, UK, Plantlife. URL. Accessed May 10, 2016. http://www.plantlife.org.uk/uploads/documents/New_Priorities_for_Arable_Plant_Conservation.pdf
- Stoate, C., N. D. Boatman, R. J. Borralho, C. Carvalho, G. R. Snoo, and P. Eden. 2001. "Ecological Impacts of Arable Intensification in Europe." *Journal of Environmental Management* 63: 337–365.
- Stoate, C., A. Baldi, P. Beja, N. D. Boatman, I. Herzon, A. van Doorn, G. R. de Snoo, L. Rakosy, and C. Ramwell. 2009. "Ecological Impacts of Early 21st Century Agricultural Change in Europe - a Review." *Journal of Environmental Management* 91: 22–46.
- Stolze, M., A. Piör, A. M. Häring, and S. Dabbert. 2000. "Environmental Impacts of Organic Farming in Europe." In *Organic Farming in Europe: Economics and Policy* 6. Stuttgart: University of Hohenheim.
- Storkey, J., S. R. Moss, and J. W. Cussans. 2010. "Using Assembly Theory to Explain Changes in a Weed Flora in Response to Agricultural Intensification." *Weed Science* 58: 39–46.
- Storkey, J., S. Meyer, K. S. Still, and C. Leuschner. 2012. "The Impact of Agricultural Intensification and Land-Use Change on the European Arable Flora." *Proceedings of the Royal Society B* 279: 1421–1429.
- Stroh, P. A., S. J. Leach, T. A. August, K. J. Walker, D. A. Pearman, F. J. Rumsey, C. A. Harrower, et al. 2014. *A Vascular Plant Red List for England*. Bristol, UK: Botanical Society of Britain and Ireland.
- Sutcliffe, O. S., and Q. O. N. Kay. 2000. "Changes in the Arable Flora of Central Southern England since the 1960s." *Biological Conservation* 93: 1–8.
- Svensson, R., and M. Wigren. 1982. "Några ogräsarter tillbakagång belyst genom konkurrens-, gödslings- och herbicidförsök [Decline of Some Weed Species Highlighted by Competition, Fertilization and Herbicide Trials]." *Svensk Botanisk Tidskrift* 76: 241–258.
- Takács-György, K., and I. Takács. 2012. "Changes in Cereal Land Use and Production Level in the European Union

- during the Period 1999–2009, Focusing on New Member States.” *Studies in Agricultural Economics* 114: 24–30.
- The Plant List. Version 1.1. 2013. Accessed May 10, 2016. <http://www.theplantlist.org/>
- Thomann, M., E. Imbert, R. C. Engstrand, and P. O. Cheptou. 2015. “Contemporary Evolution of Plant Reproductive Strategies under Global Change is Revealed by Stored Seeds.” *Journal of Evolutionary Biology* 28: 766–778.
- Thompson, K., S. R. Band, and J. G. Hodgson. 1993. “Seed Size and Shape Predict Persistence in Soil.” *Functional Ecology* 7: 236–241.
- Timmons, F. L. 2005. “History of Weed Control in the United States and Canada.” *Weed Science* 53: 748–761.
- Torresen, K. S. 2003. “Relationship between Seedbanks and Emerged Seeds in Long Term Tillage Experiments.” *Aspects of Applied Biology* 51: 55–62.
- Torresen, K. S., and R. Skuterud. 2002. “Plant Protection in Spring Cereal Production with Reduced Tillage. IV. Changes in the Weed Flora and Weed Seedbank.” *Plant Protection* 21: 179–193.
- Toth, A., G. Benecs-Bardi, and G. Balazs. 1999. “Results of National Weed Surveys in Arable Land during the past 50 Years in Hungary.” In *Proceedings 1999 Brighton Crop Protection Conference – Weeds*, 805–810. 15–18 November 1999. Brighton: The British Crop Protection Council.
- Tscharntke, T., H. -J. Greiler, I. Dewenter, A. Kruess, A. Gathmann, J. Zabel, J. Wesseling, M. Dubbert, J. Kuhnhenne, and M.-H. Vu. 1996. “Die Flächenstilllegung in der Landwirtschaft – eine Chance für die Flora und Fauna der Agrarlandschaft? [Set-aside in Agriculture – a Chance for the Flora and Fauna of the Agricultural Landscape?].” *NNA-Berichte* 2 (96): 59–72.
- Tscharntke, T., A. M. Klein, A. Kruess, I. Steffan-Dewenter, and C. Thies. 2005. “Landscape Perspectives on Agricultural Intensification and Biodiversity-Ecosystem Service Management.” *Ecology Letters* 8: 857–874.
- Türe, C., and H. Böcük. 2008. “Investigation of Threatened Arable Weeds and Their Conservation Status in Turkey.” *Weed Research* 48: 289–296.
- Ulber, L., H. H. Steinmann, and S. Klimek. 2010. “Using Selective Herbicides to Manage Beneficial and Rare Weed Species in Winter Wheat.” *Journal of Plant Diseases and Protection* 117: 233–239.
- Verlaque, R., and D. Filosa. 1997. “Caryologie et biogéographie des messicoles menacées du Sud-Est de la France (Comparaison Avec Les Autres Mauvaises Herbes) [Caryology and Biogeography of Threatened Arable Plants of Southwestern France (Comparison with other Arable Weeds)].” *Faut-il sauver les mauvaises herbes? Colloquium at Conservatoire Botanique National de Gap-Charance*, edited by J. P. Dalmas, 105–124.
- Vigueira, C. C., K. M. Olsen, and A. L. Caicedo. 2013. “The Red Queen in the Corn: Agricultural Weeds as Models of Rapid Adaptive Evolution.” *Heredity* 110: 303–311.
- Wagner, M., R. F. Pywell, T. Knopp, J. M. Bullock, and M. S. Heard. 2011. “The Germination Niches of Grassland Species Targeted for Restoration: Effects of Seed Pre-Treatments.” *Seed Science Research* 21: 117–131.
- Wagner, M., J. W. Redhead, M. Nowakowski, C. H. Shellswell, J. M. Bullock, and R. F. Pywell. 2013. “Effects of Cultivation and Herbicide Application Regimes on the Plant Species Composition of Uncropped Arable Margins.” *Aspects of Applied Biology* 118: 127–136.
- Wäldchen, J., J. Pusch, and V. Luthardt. 2005. “Zur Diasporen-Keimfähigkeit von Segetalpflanzen [Diaspore Germination Capacity of Weed Seeds].” *Beiträge zur Forstwirtschaft und Landschaftsökologie* 38: 145–156.
- Waldhardt, R. 1994. *Flächenstilllegung und Extensivierung im Ackerbau – Flora, Vegetation und Stickstoff-Haushalt* [Set-aside and Extensification of Arable Land – Flora, Vegetation, and Nitrogen Balance]. Siegen: Vorländer.
- Walker, K. J., C. N. R. Critchley, A. J. Sherwood, R. Large, P. Nuttall, S. Hulmes, R. Rose et al. 2006. “Effectiveness of New Agri-Environment Schemes in Conserving Arable Plants in Intensively Farmed Landscapes.” *Defra Cereal Field Margin Evaluation, Phase 3: Evaluation of Agri-Environment Cultivated Options in England*. UK Department for Environment, Food and Rural Affairs.
- Walker, K. J., C. N. R. Critchley, A. J. Sherwood, R. Large, P. Nuttall, S. Hulmes, R. Rose, and J. O. Mountford. 2007. “The Conservation of Arable Plants on Cereal Field Margins: An Assessment of New Agri-Environment Scheme Options in England, UK.” *Biological Conservation* 136: 260–270.
- Weibull, A. C., O. Ostman, and A. Granqvist. 2003. “Species Richness in Agroecosystems: The Effect of Landscape, Habitat and Farm Management.” *Biodiversity and Conservation* 12: 1335–1355.
- Weil, R. R. 1982. “Maize-Weed Competition and Soil Erosion in Unweeded Maize.” *Tropical Agriculture* 59: 207–213.
- Wicke, G. 1998. “Stand der Ackerrandstreifenprogramme in Deutschland [State of Field Margins Programs in Germany].” *Schriftenreihe Landesanstalt für Pflanzenbau und Pflanzenschutz (Mainz)* 6: 55–84.
- Willcox, G. 2012. “Searching for the Origins of Arable Weeds in the near East.” *Vegetation History and Archaeobotany* 21: 163–167.
- Willerding, U. 1986. *Zur Geschichte der Ackerunkrauter Mitteleuropas* [The History of Arable Plants in Central Europe]. Göttinger Schriften zur Vor- und Frühgeschichte 22. Neumünster: Wachholtz Verlag.
- Wilson, P. J. 1990. *The Ecology and Conservation of Rare Arable Weed Species and Communities*. PhD diss., University of Southampton.
- Wilson, P. J. 1992. “The Natural Regeneration of Vegetation under Set-aside in Southern England.” In *Set-aside*, edited by J. Clarke. British Crop Protection Council Monographs 50: 73–78.
- Wilson, P. J. 1994. “Managing Field Margins for the Conservation of the Arable Flora.” In *Field Margins – Integrating Agriculture and Conservation*, edited by N. D. Boatman. British Crop Protection Council Monographs 58: 253–259.
- Wilson, P. J. 1999. “The Effect of Nitrogen on Populations of Rare Arable Plants in Britain.” *Aspects of Applied Biology* 54: 93–100.
- Wilson, P. J. 2007a. “Important Arable Plant Areas – Criteria for the Assessment of Arable Sites.” *Aspects of Applied Biology* 81: 183–189.
- Wilson, P. J. 2007b. “The Status of *Centaurea cyanus* in Britain.” Plantlife, Salisbury, UK. URL. Accessed May 10, 2016. [http://www.plantlife.org.uk/uploads/documents/WilsonP\(2007\)The-Status-of-Centaurea-cyanus-in-Britain.pdf](http://www.plantlife.org.uk/uploads/documents/WilsonP(2007)The-Status-of-Centaurea-cyanus-in-Britain.pdf)
- Wilson, P. J., and N. J. Aebischer. 1995. “The Distribution of Dicotyledonous Arable Weeds in Relation to Distance from the Field Edge.” *Journal of Applied Ecology* 32: 295–310.

- Wilson, P. J., and M. King. 2003. *Arable Plants - a Field Guide*. Old Basing, UK: English Nature & WildGuides.
- Wilson, P. J., N. D. Boatman, and P. J. Edwards. 1990. "Strategies for the Conservation of Endangered Arable Weeds in Great Britain." Integrated Weed Management in Cereals. Proceedings EWRS-Symposium, Helsinki, 4-6 June 1990, 93-101.
- Wolff-Straub, R. 1989. "Vergleich der Ackerwildkraut-Vegetation alternativ und konventionell bewirtschafteter Äcker [Comparison of the Arable Vegetation of Organically and Conventionally Managed Fields]." *Schriftenreihe der Landesanstalt für Ökologie, Landschaftsentwicklung und Forstplanung NRW* 11: 70-111.