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Common arable weeds in Germany support the biodiversity of arthropods and birds

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The earth's vegetation is part of a web of life in which there are intimate and essential relations between plants and the earth, between plants and other plants, between plants and animals. Sometimes we have no choice but to disturb these relationships, but we should do so thoughtfully, with full awareness that we do may have consequences remote in time and place.

- Rachel Carson, Silent Spring (1962)

Abstract

Where have all the flowers gone? The intensification of agriculture, with its more efficient weed control methods, has led to significant changes in agroecosystems. Since 1950, the biodiversity of arable weeds in crops has sunk by more than 70%. At the same time, arthropods and birds have been in steep decline across all taxa in Germany and beyond. The global biodiversity loss is occurring at an alarming rate, but what is the role of arable weeds in supporting biodiversity? And how can the knowledge of the ecological value of arable weeds be integrated into practical farming?

In this thesis, the 51 arable weed species and 3 weed genera that are most common in Germany were reviewed for their provision of food and shelter for the fauna. Direct and indirect linkages between weeds and birds as well as phytophagous arthropods, agricultural pest arthropods, natural enemies and pollinators were counted based on data from published literature. A total of 5180 linkages was counted, of which 92 arthropod species were monophagous. Based on this, several weed species of particularly high biodiversity value were identified. The highest number of linkages with arthropods was found for *Rumex acetosella*, *Cirsium arvense* and *Taraxacum officinale*. For birds, *Rumex officinalis, Raphanus raphanistra, Stellaria media, Spergula arvensis*, *Chenopodium album* and the *Polygonaceae* genus were found to be key food items.

Today, weeds are mainly regarded as economically damaging. The data from this thesis and a number of other studies indicate that a new approach to weed management is needed. Weeds do much more than impede crop production, as they support a wide range of ecosystem services. A model that takes the benefits of weeds both for biodiversity and farmers into account should be developed urgently. Several management suggestions are briefly reviewed here, but it will need a broad discussion among all stakeholders to bring about much-needed change in practical weed management and farming.

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1. Introduction

1.1 Weeds: their significance and population trend

From the beginnings of agriculture, humans have modified agroecosystems to meet their need of producing food and generating consistent, high yields. In the 20th century, significant changes have taken place in agriculture. Namely, chemical pesticides have enabled farmers to control pests and weeds more effectively. Weeds have generally been considered as undesirable in farming systems (Blanco Valdes 2016) since they interfere with crop production in various ways. Weeds compete with crops for the same resources, such as water, nutrients and light and they can be alternate hosts for crop pests and pathogens. Furthermore, weeds can interfere with combine harvesting and increase grain moisture (Zimdahl 2013, p. 25). Indeed, among all factors causing yield loss in crops, weeds produce the highest potential loss worldwide, rising up to 34% (Oerke 2006).

Until the introduction of chemical weed control, weeds were largely controlled manually or mechanically. Indirectly, weeds were also controlled through crop rotation (Stephens 1982). With the intensification of agriculture and a wide use of herbicides, significant changes in weed flora have taken place. Meyer et al. (2014) showed that both the abundance and species diversity of arable weeds have decreased dramatically since 1950.

The trend towards the simplification of weed control measures (mainly herbicides) and a reduced diversity of crop rotations and other indirect control measures are associated with a reduced diversity of arable weeds (Gerowitt 2016). In its most extreme form – herbicide-resistant crops managed with broad-spectrum herbicides – dominant herbicide-resistant weed species have emerged and wild plant diversity and abundance have been shown to decrease dramatically. (Schütte et al. 2017; Heard et al. 2003; Bohan et al. 2005). Populations of weed flora are now less diverse (Salonen et al. 2001, 2011), since weed species that are well adapted to modern farm management are increasing in frequency, whereas less adapted weed species are in decline or on the brink of extinction. The number of weed species inside of fields has sunk by 71% and some weed species that used to be very common in the past have decreased by 95-99% between 1950 and 2014 (Meyer et al. 2014). Almost one-third of the 260–300 weed species in Germany are endangered or extinct (Haase and Schmidt 1989). The most important causes of this decrease in plant species include the extended application of herbicides, reduced crop rotations, high nitrogen levels and the abandonment of cultivation on marginal locations (Haase and Schmidt 1989; Schneider et al. 1994; Hofmeister and Garve 1998; Schumacher and Schick 1998).

1.2 Biodiversity trends of arthropods and birds

Parallel to a decline in weed abundance and diversity caused by the intensification of agriculture, a biodiversity loss is occurring among higher trophic levels across the world. Is this coincidence? This question has caught the attention of a number of researchers. Particularly, Marshall et al. (2003), Hyvönen and Huusela-Veistola (2008) and Holland et al. (2005) evaluated the importance of arable weeds in supporting biodiversity at higher trophic levels on farmland. Hawes et al. (2003) and Newton (2004) demonstrated that a decline in the abundance of primary producers is linked to a decline in species at higher trophic levels.

Caballero-López et al. (2010) and Evans et al. (2011) demonstrated the link between farm management intensity and the abundance of higher trophic level species and their food plants on the farm.

It is known that weeds, just as plants generally do, play an important role in supporting arthropods and birds. 25% of known multicellular animals are insects that feed on green plants (Bernays 2009). In arable systems, fields with fewer weeds have lower insect population densities (Buckelew et al. 2000). Thus, interactions between weed communities and insects, and arthropods in general, are highly significant in terms of biodiversity and probably far more so than is generally accepted (Marshall et al. 2001). Weeds additionally serve as shelter and alter habitat conditions for arthropods in crop fields (Norris and Kogan 2005).

The diet of farmland birds mainly consists of invertebrates and seed-bearing weeds and crops (Holland et al. 2005). Therefore, birds benefit from weeds in two ways: either by directly feeding on weeds, or by feeding on arthropods or other birds that are attracted by weeds. Indeed, many bird species that are currently in decline feed on seeds and plant material as adults, but require arthropods for nourishing their chicks during the breeding season (Marshall et al. 2003). A comparison of herbicide-treated and untreated plots of winter cereal clearly demonstrated that untreated plots had greater weed density and diversity and significantly higher numbers of many invertebrate taxa, notably those that are important in the diet of farmland birds (Moreby 1999). When farmland birds have the opportunity to feed both within the crop and in adjacent non-crop areas, they often prefer to forage within the crop, as weed seeds were found to predominate in their diet (Wilson et al. 1996; Holland et al. 2005; Robinson et al. 2004).

By controlling weeds and modifying abundance and species assemblages, herbicides negatively impact non-target taxa as well (Marshall et al. 2001). Non-target taxa namely include arthropods and birds (see Fig. 1) and it is now well established that an abundance and species diversity decline is occurring across all taxa (Kosiór A. et al. 2007; Haupt et al. 2009; Brooks et al. 2012; BOJKOVÁ et al. 2012; Sánchez-Bayo and Wyckhuys 2019; Hallmann et al. 2017; van Swaay et al. 2006).

Has the connection between declines of weeds and arthropods and birds been demonstrated before? Biesmeijer et al. (2006) observed a parallel decline in pollinators and insect-pollinated plants. Wagner (2020) notes that habitat destruction and agricultural intensification (including pesticide use) are some of the major drivers of insect loss. Donald et al. (2001) and Chamberlain et al. (2000) showed that the collapse of farmland bird populations is directly linked to agricultural intensification. For grey partridge, a strong relationship was found between food availability during breeding and breeding success, which was demonstrably linked to population change (Potts G.R. and Aebischer N.J. 1991). Brickle et al. (2000) found that the weights of corn bunting nestlings were positively correlated with the abundance of chick food invertebrates; and so, farming practices that increase invertebrate availability benefit corn bunting breeding success. Schrauth and Wink (2018) found strong declines for insectivorous birds in protected areas in the Southwest of Germany. However, changes on the landscape level also play a major role in population declines of birds, more so than of arthropods. For example, Traba and Morales (2019) showed that the decline of farmland birds in Spain is strongly associated to the loss of fallow land.

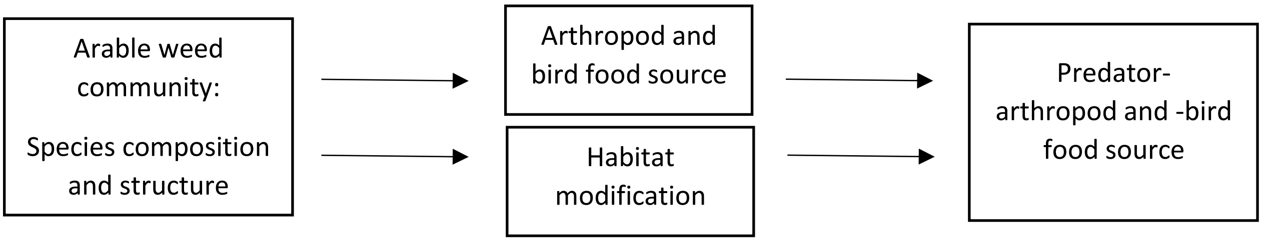

Figure 1: How arable weed communities alter field habitats and trophic relationships between plants, arthropods and birds.

While a decline in biodiversity has already been observed for several decades, recent studies showed that the exact rate of biodiversity loss has previously been underestimated. Hallmann et al. (2017) demonstrated a loss of up to 82% in insect biomass over 27 years in protected areas in Germany, which considerably exceeds the estimated decline of 58% in global abundance of wild vertebrates between 1970 and 2016 (WWF International 2016; Ceballos et al. 2017). Additionally, it needs to be considered that a decline in biodiversity had already been taking place prior to these studies (Desender and Turin 1989; Maes and van Dyck 2001; Pimm et al. 2014), which further aggravates the picture. Recent studies indicate that the biodiversity loss continues to worsen, with no turning point in sight (Pe'er et al. 2017). In light of such dramatic declines, urgent action is needed to revert these negative trends. At the same time, the need for producing more food to feed the growing human population is likely to increase (UN 2015). How can we reconcile the need to produce food with the need to preserve biodiversity? Can farming occur without bringing about a collapse in biodiversity?

1.3 Weeds as ecological goods

Ecosystems under cultivation now occupy almost two-thirds of the earth's surface (Blanco Valdes 2016). More than 50% of Germany's land area is under agricultural cultivation (Statistisches Bundesamt 2018), whereas in the UK, more than 75% of the land surface is farmed in one way or another (Marshall et al. 2003). So, merely by the amount of land area they occupy, agroecosystems and their management are a major factor impacting biodiversity and ecosystems as a whole. While they have often solely been valued for their food production capacity, attention is now increasingly shifting to their manifold ecosystem services (Power 2010; Gerowitt et al. 2003a). Ecosystem services are defined as the contributions that ecosystems make to human well-being, which ultimately translate into economic contributions as well. On the one side, ecosystems, with its biodiversity, generate economic benefits. On the other side, biodiversity losses create costs that are increasingly being recognized by economists (Hanley and Perrings 2019). According to the Common International Classification of Ecosystem Services (2018), agroecosystems provide ecosystem services such as:

- *provisioning services* (through the food, water and other resources they provide)
- *regulating services* (through regulating the quality of air and soil, or by providing flood and disease control)
- *supporting services* (through providing habitat, food and water for living beings or maintaining genetic diversity)
- *cultural services* (through their benefits for recreation, tourism etc.)

Here, the focus is on the *supporting* ecosystem services of arable weeds for the biodiversity of arthropods and birds. Weeds, in this context, are defined as plants that grow in arable systems alongside crops but have not been sown intentionally by the farmer. Biodiversity encompasses the diversity of genetic material, species and habitats (Millennium Ecosystem Assessment 2005).

Generally, plants are primary producers and an important source of food and habitat for animals such as phytophagous arthropods and birds. Arable weeds are an integral part of agroecosystems. Besides having an intrinsic value, they play a role in providing ecosystem services. Notably, weeds provide pollen and nectar for pollinators (Burkle and Alarcón 2011), serve as a source of food for phytophagous animals, act as cover crops preventing erosion and nutrient leaching (Zimdahl 2013, p. 65), represent a genetic resource and generally provide habitat for farmland wildlife (Zwerger and Ammon 2002, pp. 14–19). Weeds are indicators of the overall diversity of the agroecosystem (see also Fig. 1). It can be said that the number of plant species in an ecosystem correlates with the number of species on higher trophic levels, such as arthropods and birds (Obrist and Duelli 1998).

By attracting beneficial arthropods, weeds support biological pest control in the field (Blanco Valdes and Leyva 2007; Basedow 1988; Nentwig 1994; Norris and Kogan 2005). Beneficial insects are more likely to find alternative preys, shelter and places for reproduction when a diverse weed flora is present (Thurston 1992). Phytophagous arthropods feeding on weeds can serve as a food source for beneficial predator arthropods. In this way, weeds can indirectly serve as a resource for such beneficials within the food web (Norris and Kogan 2005). Furthermore, weeds can serve as alternative hosts to arthropod pests, as in the case of e.g. *Amaranthus viridis*, which is an alternative aphid host and thus considerably lowers transmissions of viral diseases (Caballero and Montes 1994). In other cases, damage from insect pests has been reduced when there was a diverse weedy coverage in corn crops, as opposed to fields that were weed-free (Sagar 1974).

Generally, biodiversity has been shown to reduce pest pressure and render agroecosystems more resilient and self-regulating (Altieri and Nicholls 2004). A positive correlation has been observed between species numbers and improved ecosystem functioning and productivity (Hooper et al. 2005). The more diverse and complex the agroecosystem, the more stable and productive it is and the less vulnerable it is to pests and other ecological disruptions (Nicholls 2008; Walter 2011; Estevez et al. 2000).

Nevertheless, the value of weeds is not being given enough consideration in practical farming. In spite of an increasing awareness of the economic and ecological value of biodiversity and of the parallel staggering biodiversity loss we are experiencing, farmers still view weeds mostly from the perspective of their economic damage. This is obvious from the decision-making system for the use of herbicides that is currently employed in conventional farming in Germany. The decision whether to spray herbicides or not is often based on an economic threshold. This economic weed density threshold is defined as the density at which the costs of a herbicide application equal the monetary loss due to the yield loss caused by the weed infestation (Gerowitt and Heitefuss 1990). This model did not take the ecosystem services of weeds into account. Weeds have an ecological value that results in an economic value both for farmers and for society. Biodiversity being a public good, the ecosystem services resulting from biodiversity should also be rewarded as such on the farm-level (Gerowitt et al. 2003b).

This is in accordance with the Strategy for Sustainability issued by the German Federal Government, whose goal it is, among others, to revert the trend of biodiversity loss and restore the biodiversity level of 1995 (Bundesregierung 2016). Furthermore, the German Federal Government stipulates sustainable weed management practices which aims at reducing pesticide inputs and integrating the preservation of biodiversity in the field and in agricultural landscapes in general (BMEL 2013; Bundesregierung 2016).

1.4 Research objectives

The aim of this thesis is to demonstrate the value of arable weeds for the biodiversity arthropods and birds. Specifically, linkages between the most common arable weeds in Germany and pollinating and phytophagous arthropods, agricultural arthropod pests and their natural enemies and birds are counted and examined. Studies that have been done on this topic before either focused on a limited number of arable weeds, on few recipient categories only or did not investigate until the species level (Marshall et al. 2001; Marshall et al. 2003; Holland et al. 2005; Hyvönen and Huusela-Veistola 2008). Furthermore, recent studies indicate that the current biodiversity loss, especially for insects, has been underestimated before (Hallmann et al. 2017). This makes it clear that there is an urgent need to further investigate the role of arable weeds in supporting the biodiversity of fauna, preparing the way to meet the goals of the German Strategy for Sustainability (Bundesregierung 2016) and the EU Biodiversity Strategy for 2030 (European Comission 2020).

The hypothesis presented here is that arable weeds have an important role for biodiversity that exceeds their economic damage. Their value has previously been underestimated or ignored in practical farming by focusing solely on their economic damage in terms of the economic weed density threshold. So, to change this approach, the value of weed abundance and species diversity for higher trophic levels and therefore for agroecosystems and farmers in general, is discussed.

An assemblage of 51 weed species and 3 weed genera were selected for the study (see Table 1). The selected weed species represent the most common weeds on arable fields in Germany and they were selected based on the experience of Prof Dr sc agr Bärbel Gerowitt. The species nomenclature follows the binomial nomenclature but omits the use of name-givers to ensure better readability.

Table 1: List of reviewed weed species and genera with their botanical names and EPPO code.

Botanical name	EPPO code
Aphanes arvensis	APHAR
Alopecurus myosuroides	ALOMY
Thlaspi arvense	THLAR
Veronica hederifolia	VERHE
Veronica agrestis	VERAG
Veronica	1VERG
Sonchus arvensis	SONAR
Sonchus oleraceus	SONOL
Chenopodium album	CHEAL
Raphanus raphanistrum	RAPRA
Capsella bursa-pastoris	CAPBP
Aethusa cynapium	AETCY
Matricaria inodora	MATIN
Matricaria	1MATG
Galium aparine	GALAP
Persicaria lapathifolia	POLLA
Polygonum persicaria	POLPE
Polygonum aviculare	POLAV
Fallopia convolvulus	POLCO
Centaurea cyanus	CENCY
Cirsium arvense	CIRAR
Senecio vulgaris	SENVU
Anchusa arvensis	LYCAR
Lactuca serriola	LACSE
Papaver rhoeas	PAPRH
Elymus repens	AGGRE
Lapsana communis	LAPCO
Descurainia sophia	DESSO
Sisymbrium officinale	SSYOF
Poa annua	POAAN
Chrysanthemu segetum	CHYSE
Arabidopsis thaliana	ARBTH
Sinapis arvensis	SINAR
Spergula arvensis	SPRAR
Lithospermum arvense	LITAR
Viola arvensis	VIOAR
Geranium dissectum	GERDI

Lamium purpureum	LAMPU
Bromus sterilis	BROST
Myosotis arvensis	MYOAR
Stellaria media	STEME
Lolium perenne	LOLPE
Convolvulus arvensis	CONAR
Apera spica-venti	APESV
Vicia	1VICG
Euphorbia helioscopia	EPHHE
Echinochloa crus-galli	ECHCG
Solanum nigrum	SOLNI
Setaria viridis	SETVI
Digitaria sanguinalis	DIGSA
Amaranthus retroflexus	AMARE
Rumex acetosella	RUMAA
Taraxacum officinale	TAROF

Next, a literature review was conducted for the weeds species in order to determine their value for arthropods and birds in a comparable manner. To measure the value of the weeds for arthropods and birds, linkages between host plants and arthropods/birds were counted (Marshall et al. 2003). It was differentiated between direct and indirect linkages. For arthropods, only direct linkages were reviewed (i.e. arthropods of all life stages directly feeding/living on any part of the plant). For birds, both direct linkages (i.e. birds feeding on any part of the plant), as well as indirect linkages (predator birds feeding on birds that are directly linked to the host plant) were reviewed.

The data on linkages was obtained from published literature and databases. Data from Germany was preferred, but other European and non-European sources were included as well. The *Handbuch der Segetalpflanzen Mitteleuropas* (Kästner et al. 2001), which focuses on arable weeds in Germany, Austria and Switzerland, offered substantial information on plant-insect interactions but focused mainly on phytophagous insects. Likewise, the Database of British Insects and their Food Plants (UK Centre for Ecology and Hydrology 2008), formerly known as PIDB, contained extensive data on linkages between phytophagous insects and their host plants. The DBIF was developed by the Centre for Ecology and Hydrology, UK and is the most exhaustive database of this kind for British insect species and their food plants (Ward 1988; Ward and Spalding 1993), containing some 50,000 linkages (Hyvönen and Huusela-Veistola 2008). This data was sourced from the literature, museum collections and from unpublished sources (Marshall et al. 2003), mostly compiled from the UK, but also including information from other European countries.

Both the *Handbuch der Segetalpflanzen Mitteleuropas* and the DBIF lacked information on pollinating insects, but this weakness was to some extent compensated by the information on pollinators found in Altieri et al. (2015), Elfving (1968) and the LEPIDAT database (BfN 2000). Altieri et al. (2015) compiled information on the interaction between crops, weeds and pollinators. Information on the flower visits of wild bees (*Hymenoptera: Apoidea*) to the plant species was obtained from Elfving (1968), as found in Hyvönen and Huusela-Veistola (2008). The LEPIDAT database is the Federal Agency for Nature Conservation's data bank for butterflies and moths and it contains extensive information on both phytophagous and pollinating insects of the *Lepidoptera* order and their host plants in Germany (Pretscher and Kleifges 2000). The LEPIDAT database is accessible online on the platform FloraWeb and its data is sourced from published literature. Furthermore, information on arthropod-weed linkages was obtained from Petit et al. (2011) who focused on seed predation by carabid beetles for 12 weed species, as well as from Norris and Kogan (2005).

Information on bird-plant linkages was obtained from Holland et al. (2005), Clarke R. et al. (2003) and the book series of The Birds of The Western Palearctic (Cramp 1983, 1985, 1988; Cramp, S., Brooks D.J. 1992; Cramp, S., Perrins C.M. 1994; Cramp, S., Perrins, C.M. 1996), as seen in Hyvönen and Huusela-Veistola (2008).

Finally, the Encyclopaedia of Life or EOL (National Museum of Natural History Smithsonian 2018) offered information on both arthropod-plant and bird-plant linkages and allowed to trace back linkages between birds and their bird predators, thus being the source of information on indirect bird-plant linkages. EOL is an open access platform that provides knowledge on biodiversity, integrating data bases and open data hubs from around the world. The institutions that participate in EOL are Smithsonian Institution's National Museum of Natural History, Marine Biological Laboratory and New Library of Alexandria and they collaborate with a multitude of data sharing platforms, museums, publishers and science communities.

Since the information on linkages with host plants form the various reviewed sources sometimes overlapped, multiple references to the same recipient species were omitted. After reviewing all the above-mentioned sources, the number of linkages was counted for each weed species/genus using Microsoft Excel. Monophagous arthropods were counted separately. Furthermore, the arthropod category was divided into natural enemies of arthropod pests, phytophagous arthropods, agriculturally significant arthropod pest species and pollinators. Information on the respective category for each arthropod species was obtained from the reviewed literature as well as through online research.

3. Results

The finished data base consisted of 51 weed species and 3 weed genera that were linked to a total of 5180 arthropod and bird species (Table 2). The number of linkages between host plants and recipients (i.e. arthropods and birds) varied among the weed species and genera studied. Some weed species were host plants to a significant number of arthropods or birds, whereas other weed species were of low significance to recipient species. Some weed species were not included in the diet of birds at all. Since species diversity is generally higher among arthropods, linkages with arthropods were consequently more numerous. However, three weed species were more important for birds than for arthropods (*Fallopia convolvulus, Spergula arvensis* and *Amaranthus retroflexus*).

Particularly important weed species for arthropods (more than 200 linkages per host plant) were *Rumex acetosella*, *Taraxacum officinale*, *Cirsium arvense* and *Poa annua*. *Rumex acetosella* also showed the greatest number of linkages with birds, followed by *Fallopia convolvulus, Polygonum aviculare, Chenopodium album, Spergula arvensis, Stellaria media, Geranium dissectum, Lamium purpureum* and *Persicaria lapathifolia* (each more than 30 associated bird species).

Table 2: Total number of linkages between weed species (or genera) and arthropods and birds.

	Arthropods	Birds
	Number of linkages	
Aphanes arvensis	28	0
Alopecurus myosuroides	80	0
Thlaspi arvense	37	10
Veronica hederifolia	48	0
Veronica agrestis	50	0
Veronica	82	6
Sonchus arvensis	91	18
Sonchus oleraceus	76	19
Chenopodium album	58	37
Raphanus raphanistrum	68	27
Capsella bursa-pastoris	70	7
Aethusa cynapium	10	0
Matricaria inodora	100	1
Matricaria	74	1
Galium aparine	169	8
Persicaria lapathifolia	80	31
Polygonum persicaria	80	33
Polygonum aviculare	176	39
Fallopia convolvulus	15	40
Centaurea cyanus	112	13
Cirsium arvense	295	18
Senecio vulgaris	109	26
Anchusa arvensis	26	0

Lactuca serriola	45	25
Papaver rhoeas	25	0
Elymus repens	59	2
Lapsana communis	33	2
Descurainia sophia	40	0
Sisymbrium officinale	55	0
Poa annua	203	16
Chrysanthemu segetum	88	0
Arabidopsis thaliana	25	0
Sinapis arvensis	105	18
Spergula arvensis	21	33
Lithospermum arvense	18	0
Viola arvensis	65	13
Geranium dissectum	35	30
Lamium purpureum	100	30
Bromus sterilis	39	0
Myosotis arvensis	38	7
Stellaria media	142	31
Lolium perenne	68	22
Convolvulus arvensis	104	17
Apera spica-venti	67	0
Vicia	185	0
Euphorbia helioscopia	70	1
Echinochloa crus-galli	72	22
Solanum nigrum	47	5
Setaria viridis	75	25
Digitaria sanguinalis	68	25
Amaranthus retroflexus	20	24
Rumex acetosella	308	43
Taraxacum officinale	285	14

A number of arthropod species are dependent on specific weeds to complete their life cycle. 25 weed species and 1 weed genus were hosts to a total of 92 monophagous arthropod species, listed in Table 3. The information on monophagous arthropods was derived from the *Handbuch der Segetalpflanzen Mitteleuropas* and the DBIF. While most weed species are associated with only one monophagous arthropod species, *Raphanus raphanistrum* and *Spergula arvensis* stand out as hosts of numerous host-specific arthropod species, followed in significance for monophagous arthropods by *Rumex acetosella*, *Cirsium arvense* and *Polygonum aviculare*.

Table 3: Number of monophagous arthropods and their host plants.

	Monophagous Arthropods
Thlaspi arvense	1
Sonchus arvensis	1
Chenopodium album	1
Raphanus raphanistrum	23
Capsella bursa-pastoris	1
Aethusa cynapium	2
Galium aparine	1
Persicaria lapathifolia	3
Polygonum persicaria	1
Polygonum aviculare	4
Cirsium arvense	6
Elymus repens	1
Lapsana communis	3
Descurainia sophia	1
Poa annua	1
Arabidopsis thaliana	1
Spergula arvensis	24
Bromus sterilis	1
Myosotis arvensis	1
Stellaria media	1
Lolium perenne	1
Convolvulus arvensis	1
Vicia	1
Solanum nigrum	1
Rumex acetosella	9
Taraxacum officinale	1

The value of weeds also varied significantly in terms of arthropod categories linked to them (Table 4). The most numerous arthropod category was the group of phytophagous arthropods, as they were also listed in the two most extensive data sources (*Handbuch der Segetalpflanzen Mitteleuropas* and DBIF). *Taraxacum officinale, Cirsium arvense* and *Capsella bursa-pastoris* were particularly abundant in natural enemies (i.e. arthropods that feed on arthropod pest species). As for arthropod pest species, only agriculturally relevant species were reviewed. *Poa annua* was the most important weed species for arthropod pests. The weed species with the most outstanding value for a wide range of pollinating arthropods was *Cirsium arvense*, with 107 different arthropods visiting its flowers. Other host plants that were found to be particularly relevant for pollinators were *Taraxacum officinale*, the *Vicia* genus, *Sinapis arvensis* and *Raphanus raphanistrum.*

The weed species that were part of the largest number of birds' diet were *Spergula arvensis, Rumex acetosella, Chenopodium album, Stellaria media* and *Raphanus raphanistrum.* Those weed species that were food for birds also noted more indirect bird linkages (i.e. predator birds which feed on phytophagous birds).

Table 4: Number of arthropods listed as natural enemies, phytophagous arthropods, pest arthropods and pollinators linked to the weed species and number of directly and indirectly linked birds with their host plants.

	Natural enemy	Phyto-phagous	Pest arthropod	Pollinator	Bird	
					direct	Indirect
Aphanes arvensis	0	26	2	0	0	0
Alopecurus myosuroides	3	48	26	3	0	0
Thlaspi arvense	1	17	12	7	6	4
Veronica hederifolia	3	32	11	2	0	0
Veronica agrestis	3	33	12	2	0	0
Veronica	5	57	16	4	1	5
Sonchus arvensis	2	55	10	24	8	10
Sonchus oleraceus	3	51	16	6	2	17
Chenopodium album	3	40	8	7	20	17
Raphanus raphanistrum	0	21	19	28	26	1
Capsella bursa-pastoris	10	40	13	7	7	0
Aethusa cynapium	0	7	2	1	0	0
Matricaria inodora	3	70	16	11	1	0
Matricaria	2	47	12	13	1	0
Galium aparine	0	147	3	19	8	0
Persicaria lapathifolia	2	58	8	12	6	25
Polygonum persicaria	4	61	9	6	11	22
Polygonum aviculare	2	139	11	24	9	30
Fallopia convolvulus	0	12	2	1	13	27
Centaurea cyanus	3	74	7	28	1	12
Cirsium arvense	14	158	16	107	8	10
Senecio vulgaris	8	79	8	14	6	20
Anchusa arvensis	3	19	3	1	0	0
Lactuca serriola	0	36	6	3	4	21
Papaver rhoeas	1	14	6	4	0	0
Elymus repens	0	49	5	5	2	0
Lapsana communis	0	16	4	13	2	0
Descurainia sophia	0	23	11	6	0	0
Sisymbrium officinale	0	35	16	4	0	0
Poa annua	3	150	34	16	6	10
Chrysanthemu segetum	2	62	17	7	0	0
Arabidopsis thaliana	0	15	9	1	0	0
Sinapis arvensis	0	49	26	30	6	12
Spergula arvensis	0	14	5	2	33	0
Lithospermum arvense	5	11	2	0	0	0
Viola arvensis	2	49	6	8	13	0
Geranium dissectum	0	28	5	2	5	25
Lamium purpureum	0	73	5	22	5	25
Bromus sterilis	0	35	3	1	0	0
Myosotis arvensis	4	25	2	7	7	0
Stellaria media	7	113	7	15	21	10
Lolium perenne	0	63	5	0	4	18
Convolvulus arvensis	6	76	15	7	5	12

Apera spica-venti	3	36	25	3	0	0
Vicia	2	136	16	31	0	0
Euphorbia helioscopia	7	48	5	10	1	0
Echinochloa crus-galli	3	35	26	8	3	19
Solanum nigrum	1	34	9	3	3	2
Setaria viridis	2	43	27	3	7	18
Digitaria sanguinalis	2	37	25	4	1	24
Amaranthus retroflexus	1	10	8	1	9	15
Rumex acetosella	1	278	13	16	20	23
Taraxacum officinale	16	201	12	56	4	10

4. Discussion

This thesis aimed to create a data base of arthropods and birds that are linked to the 54 most common arable weeds in Germany. As part of the project “Schadschwelle Plus”, this data base will be used to develop a new economic weed density threshold extended by an ecological component. This ecological component will mainly focus on the supporting ecosystem services of weeds with regards to arthropods and birds. For a more precise perception of the ecological value of different arable weeds, linkages between weed species and arthropods and birds, respectively, were reviewed from the literature and counted. These linkages were not weighed for their relative importance for the fauna.

Recipient categories (i.e. arthropods and birds) were divided into subcategories. Arthropods were divided into natural enemies of pests (i.e. predator arthropods), phytophagous arthropods (i.e. arthropods feeding on any part of the plant), agricultural arthropod pest species and pollinators (i.e. arthropods feeding on nectar or pollen). For birds, it was differentiated between direct and indirect linkages.

It needs to be noted that not all arthropods feeding on nectar or pollen necessarily are pollinators; however, since this is the case for most pollinators as well as for simplicity reasons, this definition was used to determine pollinators. Some arthropods fall into two categories, depending on which life cycle they are in (e.g. *Syrphidae* act both as pollinators and natural enemies); for consistency reasons, only one category was chosen for each recipient species. Given that a majority of all existing arthropod species has not yet been described, the real number of arthropod species could potentially be up to 10 times higher. The true number of arthropod species is estimated to be 5-10 million, as opposed to the currently less than 1 million species described (Ødegaard 2000). Also, for some weed species, less information was available from the literature, which could lead to an underestimation of their real ecological value. Since phytophagous and pest arthropods were generally the best documented group of arthropods compared to the other groups, the number of pollinators and natural enemies could potentially be higher in reality.

Another important notice is that only weed-arthropod, weed-bird and bird-bird linkages were counted. Linkages between arthropods and birds were not reviewed, as there is few data on arthropod preferences in bird diets (Holland et al. 2005). Since arthropods hosted by arable weeds are an important source of food for birds, especially for chicks during breeding season (Marshall et al. 2001), weeds potentially have an even higher indirect value for birds. All of this should be taken into consideration when interpreting the data.

In summary, the results of this review show that arable weeds indeed have an important role for biodiversity by supporting a significant number of arthropod and bird species, including several monophagous species. Thus, a decline in weed diversity and abundance due to an intensification of agriculture leads to a reduction in their ecosystem services. It is highly likely that this decline negatively impacts the biodiversity of arthropods and birds. In the following section, I will discuss key weed species that should be maintained for biodiversity according to the resulting data and weed species that should be controlled. Following the identification of individual weed species, the need to find ways to balance crop production and biodiversity on the farm-level will be outlined. Next, practical possibilities and weed management suggestions to enhance biodiversity in farming will be reviewed. Finally, key areas for further research will be highlighted.

4.1 Identifying key weed species

5180 linkages were listed for 51 weed species and 3 weed genera. These linkages were distributed unevenly between host plants, which allows to outline weed species that are more and those that are less important for the different recipient categories. *Rumex acetosella* was found to have the greatest number of linkages both with arthropods (including 9 monophagous species) and birds. The greatest variability in linkages was observed for monophagous arthropods (92 monophagous arthropods were counted in total). While about half of all reviewed weed species host at least one monophagous arthropod, *Raphanus raphanistrum* and *Spergula arvensis* seem to be of particular importance for host-specific species. Clearly, weed species that host monophagous arthropods are especially relevant from the perspective of nature conservation. Interestingly, both of these weed species were found to be important for birds as well, though Marshall et al. (2003) lists *Spergula* only as "present" in farmland bird diet. Other weed species that should be maintained in the field as a source of food for many different bird species are *Chenopodium album* and *Stellaria media*. In addition to these, Holland et al. (2005) mentions *Viola arvensis* and Hyvönen and Huusela-Veistola (2008) and Marshall et al. (2003) highlight annual weed species that are able to produce numerous seeds, such as species from the *Polygonaceae* genus, as key food plants for birds.

Weed species that were generally abundant in arthropod species (besides *Rumex acetosella*) were *Taraxacum officinale*, *Cirsium arvense* and *Poa annua*. Marshall et al. (2003) found *Stellaria media* to be host to the greatest number of phytophagous insect species, whereas Hyvönen and Huusela-Veistola (2008) mention *Elymus repens* and *Galium species* as important insect hosts – however, both of these studies did not sum up all arthropod categories into one figure and reviewed a smaller scope of weed species.

With the ongoing discussion about the importance of pollinators and their rapid decline in many parts of the world (Biesmeijer et al. 2006; Potts et al. 2010; Cameron et al. 2011), it is especially interesting to look at weed species that are important for pollinating arthropods. Since the literature available on weed-pollinator linkages is not as extensive, these results should be interpreted with caution. Only three of the reviewed weed species did not show any linkages with pollinators, for two of which there was generally relatively little information on linkages available (*Aphanes arvensis* and *Lithospermum arvense).* Of course, it is mostly flowering plants that play an important role for pollinators, but wind-pollinated grasses are also visited by some beetles feeding on pollen. From this literature review, *Cirsium arvense*, *Taraxacum officinale*, the *Vicia* genus, *Sinapis arvensis* and *Raphanus raphanistrum* seemed to be particularly important for pollinators. Hyvönen and Huusela-Veistola (2008) additionally highlight *Sonchus arvensis* as important for wild bees. Marshall et al. (2001) emphasizes *Centaurea cyanus, Chrysanthemum segetum, Senecio vulgaris* and species from the *Matricaria* genus as species supporting the largest diversity of nectar and pollen feeding insects.

Another relevant topic in sustainable farming today are natural enemies and their use for biological pest control. Here, *Taraxacum officinale*, *Cirsium arvense* and *Capsella bursa-pastoris* seem to play an important role. However, the number of natural enemies associated with a weed might not equal the true importance of a particular weed species for biological pest control. Some weed species, such as *Centaurea cyanus*, are associated with relatively few natural enemies (which is also due to the above-mentioned problem of several arthropods falling into two categories simultaneously and therefore some natural enemies being listed as "pollinator" and not "natural enemy"). *Centaurea cyanus* has been observed to especially attract adult hoverflies (*Syrphidae*), probably due to its bright blue colour. *Syrphidae* are among the most important aphidophagous insects (Weiss and Stettmer 1991). Their larvae can devour several hundred aphids during their larval stage. When *C. cyanus* is present in the field, *Syrphidae* can be attracted even from larger distances. Once *Syrphidae* are established in the field, they also visit the flowers of *Capsella bursa-pastoris* and *Veronica persica*, which ensures their long-term presence in the field, the development of multiple larval stages per year and therefore more effective biological pest control of aphids (Nentwig 1994). This also shows that it is not individual weed species alone that offer certain ecosystem services, but often a combination of several different weed species over a period of time.

Of course, not all arthropod species are desirable in crop systems; weeds can also be hosts to a wide range of agricultural pest arthropod species. In particular, this is the case with *Poa annua*, being the host to the largest number of pest arthropods in this review. Grasses generally seem to be more important for pest arthropods than broad-leaved weeds, as almost all weed species that are hosts to a larger number of pest arthropods belong to the group of grasses. This is confirmed by Hyvönen and Huusela-Veistola (2008), who found *Elymus repens* to be the most important weed species for pest arthropods (*Poa annua* was not included in their review). In addition, Marshall et al. (2001) highlights *Sinapis arvensis* as an alternative host to many pest arthropod species, especially in *Brassicaceae* crops. It could be speculated that weeds which are alternative hosts to pest arthropod species divert pests from the main crop and could thus be regarded as beneficial. However, weeds could also attract pest arthropods to the crop in the first place, therefore amplifying their detrimental effect. Such cases have indeed been reported and Norris and Kogan (2005) suggest that weeds either maintain or increase the population of a pest arthropod capable of moving to the crop.

Broad-leaved species are generally more relevant for fauna, especially the beneficial one, than grasses. This is because invertebrates tend to prefer structurally complex species, such as herbs, over structurally simple species, such as grasses (Stinson and Brown 1983). Preference for complexity can be observed not only on the species level. Mixed weed communities provide a range of phenologies, thereby giving a range of plant structures for different invertebrate feeding types (Marshall et al. 2001). This once again highlights the importance of weed community structure over individual weed species presence. Marshall et al. (2003) also notes that for many arthropods (especially predator arthropods), vegetation density and structure may be more important than botanical composition. For some birds, landscape structure might be more important than botanical composition in the crop (Traba and Morales 2019; Stein-Bachinger et al. 2019). However, as mentioned earlier, some birds will always prefer to forage within the crop because specific weed seeds dominate in their diet (Wilson et al. 1996; Holland et al. 2005; Robinson et al. 2004) or because they tend to forage in the field centre (Vickery et al. 2002). This is especially true for birds that depend almost entirely on weed seeds. Several studies found that a shift in the diet of turtle dove (*Streptopelia turtur*) from weed seeds to crop seeds resulted in a lower fledging success. In the 1960ies, weeds seeds made up over 95% of the food eaten by turtle doves and about 80% of the nestling diet (Murton et al. 1964). In contrast, in the 1990ies weed seeds made up only 40% of adult diet and 30% of nestling diet, the balance consisting of crop seeds (Browne and Aebischer 2003). The authors concluded that this shift to lower quality food explains the lower breeding performance and therefore the population decline of turtle doves in the UK.

If weed flora arguably plays an important role for biodiversity, can we identify key weed species that should be maintained in the crop for arthropods and birds? While it should be kept in mind that vegetation and landscape structure in itself play important roles in supporting arthropods and birds, it is possible to identify weed species which are more relevant for biodiversity. Interestingly, these weed species are mostly not the main targets of weed control and have only intermediate or low competitive ability. Notably, weed species and genera of high biodiversity value are the *Vicia*, *Matricaria* and *Polygonaceae* genus, *Rumex acetosella*, *Taraxacum officinale, Cirsium arvense*, *Capsella bursa-pastoris Sinapis arvensis*, *Raphanus raphanistrum*, *Sonchus arvensis*, *Centaurea cyanus*, *Spergula arvensis*, *Poa annua*, *Galium aparine*, *Stellaria media*, *Chenopodium album* and *Senecio vulgaris.* Of course, this list is not all-exclusive, as only a fraction of the up to 300 weed species in Germany were reviewed in the first place. But it can offer some guidance and is largely in accordance with similar older reviews (Marshall et al. 2001; Hyvönen and Huusela-Veistola 2008; Holland et al. 2005; Storkey and Westbury 2007). Even more so, it offers an extended insight into the ecological value of weeds as a broader range of weed species as in the before-mentioned reviews has been examined here. Finally, the relevance of weed species will of course also depend on the respective recipients (i.e. arthropod and bird species).

4.2 Balancing biodiversity and crop production

While it is now undisputed that weeds have an ecological value, the question then is how to balance biodiversity and crop production in practical farming. Can crops and weeds co-exist to the benefit of all? Or should biodiversity targets be separated from crop production? In practical farming, some weed species must be controlled regardless of their ecological value because they seriously conflict with crop production aims on the long-term (Gerowitt et al. 2003a; Salonen et al. 2001). Whether or not a weed species is regarded as pernicious of course depends on the respective crop. But some of the most common pernicious weeds include *Alopecurus myosuroides, Bromus sterilis, Apera spica-venti, Elymus repens, Fallopia convolvulus, Galium aparine*, *Lolium perenne* and *Cirsium arvense* due to their competitiveness or persistence in the field. Perennial weeds with vegetative propagation, such as *E. repens* and *C. arvense* will usually always be regarded as targets (Reynolds et al. 2013). Other weed species, such as *Papaver rhoeas* and *Matricaria inodora,* do not have very high competitive abilities, but can potentially build up in the seed bank. To avoid massive populations of such weeds, they are often targets of weed control in cereals, as well. In oilseed rape, broad-leaved weeds such as *Stellaria media* and *Capsella bursa-pastoris* are important pernicious weeds, in sugar beet also *Chenopodium album.* In maize, *Setaria viridis* and *Echinochloa crus-galli* are among the most important weeds (IfP 2008).

The dilemma between biodiversity and crop production targets becomes obvious in the examples of *Elymus repens* and *Cirsium arvense.* The literature review showed *Elymus repens* to have relatively little significance for arthropods, while Hyvönen and Huusela-Veistola (2008) even found it to be the most important host of arthropod pests. So, while in the case of *E. repens*, the compromise in favour of crop production aims might not be very costly to biodiversity aims, the difficult balance between biodiversity and crop production aims is more evident in the case of *C. arvense* which did show to play a rather significant role as pollinator-attractor. Yet, *C. arvense* counts among the most pernicious, perennial weeds that must be maintained below an economically damaging threshold on the long-term.

Some voices, especially among farmers, therefore argue that biodiversity and crop production targets are incompatible and should best be separated spatially by maintaining crops clear of weeds and establishing separate biodiversity zones. Several agri-environmental schemes of the EU follow this approach (for example through promoting set-aside or wildflower strips). However, given the value of arable weeds demonstrated in this thesis, there are several reasons for the integration of biodiversity (i.e. weeds) into crop fields. Three major arguments that advocate this approach are: (1) the unique composition of weed flora and its relevance for the fauna, (2) the benefits of weeds, (3) the high percentage of farmed area.

(1) Weeds co-evolved with our farmland crops (Grime et al. 1982). They are not a specific taxonomic group but are rather defined by the system – the farmland – in which they grow. Weeds cannot exist outside of the arable system because they necessitate regular soil disturbance (Gerowitt 2016). As this review shows, arable weeds are hosts to a wide range of arthropods and birds, some of which are host-specific (i.e. monophagous). The supporting ecosystem services of weeds for the fauna can therefore only be upheld by maintaining weed flora within the crop.
(2) As stated earlier, arable weeds have numerous virtues in themselves, being an important component of biodiversity and contributing to the stability of the arable system (Blanco Valdes 2016; Altieri and Nicholls 2004; Hooper et al. 2005). Notably, weeds can attract pollinators (Burkle and Alarcón 2011) and natural enemies (Nentwig 1994; Basedow 1988) and reduce soil erosion (Lenka et al. 2017). A certain weedy coverage should therefore be desirable in farming systems.
(3) Farmland takes up over 50% of land area in Germany (Statistisches Bundesamt 2018). Given the dramatic biodiversity loss of recent years (Kosiór A. et al. 2007; Hallmann et al. 2017; Brooks et al. 2012), it is questionable whether these rapid declines can be sufficiently countered if crop production areas do not integrate biodiversity aims, as well. As primary producers and sources of food and shelter for higher trophic levels, the weed flora demonstrably plays an important role in safeguarding biodiversity at all levels.

This shows that maintaining at least some weeds within the crop is not only an important contribution to biodiversity targets but should also be in the interest of the farmer. This then raises another question: how can farmers manage weeds for biodiversity targets in a way that serves all the interests, particularly with arthropod and bird biodiversity in mind? The next section will explore several tools that could possibly enhance the ecosystem services of arable systems through adequate weed management.

4.3 Managing weeds for biodiversity

As outlined above, weed management methods of recent decades have led to a steep decline in their abundance in crops (Meyer et al. 2014), with the associated negative trends in the biodiversity of arthropods and birds (Marshall et al. 2001; Potts and Aebischer 1991; Caballero-López et al. 2010; Evans et al. 2011). Yet attention is also increasingly shifting towards the decline in species diversity of arable weeds. Weed species diversity is not only valuable from the perspective of nature conservation, but also a useful management tool for farmers. Uniform, simplified management tools (namely herbicides) are revealing themselves detrimental and risky as monotonous, herbicide-resistant weed populations (e.g. of *Alopecurus myosuroides*, *Apera spica-venti*) are emerging. Diverse weed populations are therefore desirable both in the interest of biodiversity and farmers (Gerowitt 2016). This is especially true for the 92 monophagous arthropod species listed in this review (and the many more oligophagous species that were not listed separately here) because they depend exclusively on one weed species for their survival. If this weed species is not present or becomes extinct, the associated monophagous species inevitably disappear along with their host plant, at least locally (Raskin 1994).

It is also interesting to note that less diverse weed populations potentially increase populations of certain pest arthropods. A wide range of different weed species potentially hosts an equally wide range of arthropods, both pests and natural enemies, making it more difficult for a particularly harmful arthropod species to develop larger populations. This has been demonstrated by Bosch (1987), who observed that the total weed eradication in sugar beet fields led to more frequent mass developments of arthropod pest populations on the crop. Sugar beet plots that were infested with *Matricaria chamomilla, Lamium purpureum* and other weed species (up to 20% weed coverage) showed a higher biodiversity of neutral or beneficial arthropods and lower population densities of several agricultural arthropod pests. Less diverse weed flora therefore leads to less efficient natural pest control (Basedow 1988; Caballero and Montes 1994; Sagar 1974; Blanco Valdes 2016). Furthermore, weed suppression that at the same time reduces the biodiversity of pollinators potentially fails to use synergies regarding pollination of crops (Altieri et al. 2015).

In this review, several key weed species and genera of particular ecological value have been identified. Along with this, it is known that a number of extremely competitive weed species listed earlier must be controlled to avoid long term conflicts with the agricultural use of farmland. While it is possible to target weed control at specific weeds (for example through the application of selective herbicides or indirectly through a wider crop rotation), selecting specific weeds of intermediate or low competitive ability “to stay” in the field seems rather difficult to achieve in practical farming. A potential solution could be to manage weeds for the highest possible diversity at acceptable population densities, instead of selecting for specific weeds. There is good evidence that a higher diversity in the farmland flora directly leads to a higher diversity of the fauna (Obrist and Duelli 1998). If the goal of weed species diversity is clear, the question then is how to achieve this. The tool for creating and maintaining a diverse weed flora is known: diversified weed management (Gerowitt 2016; Critchley et al. 2004). Five aspects will briefly be reviewed here as suggestions for managing weeds for biodiversity.

(1) Fertilisation

One major driver of the decline in weed abundance and diversity is the high input of fertilizers. Most notably nitrogen strongly influences the botanical composition of the weed flora (Schumacher and Schick 1998). Diversity is generally highest at intermediate productivity or fertility (Marshall et al. 2001). Organic arable fields, which generally have lower levels of (nitrogen) fertilisation, were even found to support a number of rare weed species. On the contrary, there was a tendency for conventional fields to support more nitrophilous weed species (Rydberg and Milberg 2000). Lower nitrogen inputs would probably select for a wider variety of weeds, including some of the weeds of high biodiversity value listed above (e.g. *Rumex acetosella*). One strategy for increasing weed species diversity could therefore be the reduction of nitrogen fertilizer inputs. Given the average nitrogen surplus of 77 kg/ha N on German farmland (Umweltbundesamt 2019), this would be a desirable goal from many other ecological and economic perspectives, as well.

(2) Herbicide treatment

Boström and Fogelfors (2002a) studied the long-term effects of herbicide-application strategies in spring-sown cereals. Their trial included a 25, 50, 75 and 100% of a full dose herbicide treatment, as well as an untreated control. Higher herbicide doses naturally resulted in lower weed densities. Interestingly, herbicide-application increased the density of difficult-to-control weed species by 24% compared with the untreated control. In contrast, the untreated control contained 30% more weed species than herbicide-treated plots. Another important finding was that there was no difference in crop yield between herbicide application at 25% and 100% of a full dose (while no herbicide application at all did reduce yield). This shows that it is possible to reduce herbicide inputs without inducing a reduction in crop yield. This approach could also lead to the desirable higher weed species richness in fields, while at the same time potentially decreasing the proportion of difficult-to-control weed species (Boström and Fogelfors 2002b).

However, these results should be regarded with some caution, as other studies have found a relaxing of herbicide treatment to encourage a massive rise in abundance of one or two rather problematic weeds. Squire et al. (2000) made an experiment in which they introduced spring sown crops to the rotation and approximately halved herbicide doses. After six years, most non-target species that were present had increased either in abundance or frequency of occurrence. At the same time, the important competitive weed species, *Alopecurus myosuroides* and *Galium aparine* were also stimulated to a high number.

A potential approach could be to determine acceptable weed population levels for each species that allows a greater diversity and certain weedy coverage to persist in the field. Then, only those species or populations that require control should be controlled by applying more selective herbicides. The trend of herbicides to control more weeds today than the herbicides several years ago definitely plays a part in the reduction of weed density and abundance (Marshall et al. 2001). From the perspective of managing weeds for biodiversity, selective herbicides are to be preferred over broad-spectrum herbicides (Storkey and Westbury 2007). An interesting, more ecologically sound alternative to chemical herbicides could also be biological weed control, which is generally always targeted at a single weed species (Ammon and Müller-Schärer 1999).

Maintaining moderate numbers of a wide range of weeds with high ecological value while controlling pernicious weeds definitely presents a difficult challenge for farmers. Especially the increasing occurrence of herbicide-resistant weed genotypes makes the pressing need for new, diversified weed management practices very clear (Harker and Clayton 2013). But the examples of Boström and Fogelfors (2002a), (2002b) show that good results are achievable in an ecologically sound way. Organic farming, which does not use herbicides at all, also shows promising ways of weed management that enhances the biodiversity both of the flora and the fauna (Stein-Bachinger et al. 2020; Stein-Bachinger et al. 2019; Sanders and Hess 2019; Gruber et al. 2000).

(3) Crop rotation and diversity

Another important factor impacting weed abundance and species diversity is the crop choice. A simple fact illustrates well that the biodiversity of weeds and cultivated crops go hand in hand: of the 30 botanical families that contain the world's worst weeds, five of them, *Poaceae, Solanaceae, Convolvulaceae, Euphorbiaceae and Fabaceae* also supply 75 % of the world's food (Grime et al. 1982). This indicates that the biodiversity of weed flora could potentially rise with a greater diversity of cultivated crops. In Germany, cereals make up over half of all arable land (Statistisches Bundesamt 2020). It should therefore not surprise us that weed species diversity has declined in Germany (Meyer et al. 2014) and that the most problematic weeds are grasses. Weeds always co-evolve and co-exist with crops.

So, to move towards the goal of greater diversity of the arable flora, a diversified crop rotation is an important instrument. With regards to the needs of arthropods and birds, a move from predominantly winter cereals towards more spring cereals would be necessary. As a study shows, a change from spring cereals to winter cereals is likely to result in a 25% reduction in weed density and species diversity. This also entailed a smaller supply of plants that are important food resources for phytophagous arthropods in winter cereals (Hald 1999). For birds, (broadleaved) weed seeds on cereal stubbles during winter months are especially important. Evans (1992), (1997) observed a population increase of cirl buntings *(Emberiza cirlus)* as a consequence of respective measures. Generally, late weed control, as opposed to autumn weed control, is desirable to ensure a greater food supply for arthropods and birds, as it allows arable weeds to be present for a longer time prior to weed control measures (Marshall et al. 2001).

(4) Tillage

Tillage (which is a form of mechanical weed control) has a major impact on both the abundance and the composition of the weed flora. Murphy et al. (2006) even found it to have the largest effect of the studied tools for promoting weed species diversity and reducing weed seed banks. Specifically, no tillage promoted the highest weed species diversity. Another study also found no-plough tillage to increase weed abundance, notably grass species (Gruber et al. 2000).

Looking back at the history of agriculture, the biodiversity of the weed flora as well as the fauna reached its peak in times prior to the introduction of herbicides, when a variety of mechanical control measures as well as a diverse crop rotation were practiced (Gerowitt 2016). Tillage, with all its different forms and timings, can therefore be a valuable tool for enriching the biodiversity of arable weeds, arthropods and birds.

(5) Other

Apart from these direct and indirect weed management tools, there is an array of other instruments, new and old, that can enhance the ecosystem services of arable weeds. There is strong evidence that they would have to take place within the arable system. As we have seen, weeds cannot exist outside of the crop. The conversion of arable fields to set aside, for example through natural regeneration, has been shown to have neutral or even negative effects on weeds of high biodiversity value (MAFF 1998).

Whereas most weeds absolutely depend on the arable system, ecosystem services for arthropods and birds can in part be offered outside of the main crop. A number of measures do not directly target the ecosystem services of arable weeds, but still benefit arthropods and birds. These will briefly be reviewed here.

For a number of bird species, other factors may play a significant role apart from the supply of certain weed species, even though they certainly present an important source of food for birds. Some farmland birds reportedly depend on fallow land (Traba and Morales 2019), most notably the skylark *(Alauda arvensis)*. To a degree, birds are able to adjust their foraging behaviour to the local availability of food resources (Robinson and Sutherland 1997). This could indicate that it is not necessary for food to be evenly distributed across the landscape, but rather in small areas of high food density. This could especially benefit species such as yellowhammer *(Emberiza citronella)* and tree sparrow (*Passer montanus)*, who positively respond to conservation headlands (i.e. unsprayed field margins). Additionally, the location of hedgerows as well as overwintering cereal stubbles play an important role in the provision of food for these birds (Robinson and Sutherland 1997).

Arthropods, on the other hand, vary significantly in their response to food abundance and distribution. Mobile arthropods will to a higher degree respond to landscape structure and to a lesser degree depend upon an even distribution of food plants within the field, as well as the botanical composition and size of the field. Contrarily, less mobile arthropods will potentially require a much more even distribution of host plants in the landscape or within the field, as their flying span is often very limited. A study indicates that there is a relationship in fields in Canada between insect diversity and the amount of woody field boundary surrounding the field. There was no relationship with insect density (Holland and Fahrig 2000).

Wildflower strips, a tool that has seen a renaissance in the past years, also seem to have positive both on arthropods and birds. Dietzel et al. (2019) reviewed 48 studies about the effects of wildflower strips and concluded that in two thirds of cases, a positive effect has been found on the abundance and species diversity of animals, especially beetles and spiders, but also other arthropods, hares and pheasants. No effects were recorded for rare insect species. Similarly, conservation headlands in the UK have been recorded to increase butterfly, grey partridge and pheasant populations (Snoo et al. 1994; Snoo et al. 1998). If no fertilizers are applied in the field margins, they also seem to support rare weed flora when (Kleijn and van der Voort 1997).

To conclude, a broad range of different agronomic tools will be necessary to ensure high levels of biodiversity. This, in turn, could lead to direct benefits for farmers. Studies which compared low and high diversity seed mixtures sown on ex-arable land, indicate that a high diversity of plants gives higher productivity and better weed suppression (Leps et al. 2001; van der Putten et al. 2000). Farmers should generally consider chemical weed control as the last resort. Besides, there is a variety of other methods to be explored, such as bi-cropping, late weed control, living mulches, crop interference, allelopathy etc. (Ammon and Müller-Schärer 1999; Jordan 1993; Andrew et al. 2015).

4.4 Conclusions and outlook

The data from this thesis gives good evidence that common arable weeds in Germany do have an important role for biodiversity that exceeds their economic damage. Herbicide treatments that are usually based on economic thresholds (calculated through yield foregone) fail to sufficiently take this ecological value for the biodiversity of arthropods and birds into account. But also given the many benefits of weeds for agroecosystems and farmers in general, there is a great need to re-evaluate weed management in farming. Increasing populations of herbicide-resistant weeds make this a pressing priority. Weed density thresholds should be extended by an ecological component. The extensive database upon which this thesis is founded can be a valuable contribution for developing such an 'ecological weed density threshold' as part of the project 'Schadschwelle+'. Beyond that, weed biodiversity should be the goal of every farmer to support sustainable weed management and to ensure the proper functioning of the agroecosystem, particularly for the higher trophic levels that are supported by weeds (Fig. 2).

Figure 2: A barley field that has not been treated with herbicides and is abundant in flowering weeds that are attractive for arthropods and birds. Photograph by Naomi Sarah Bosch

Farmers' awareness about the many benefits and threats to biodiversity today needs to be increased. The role of farmers in managing weeds for biodiversity should increasingly become part of farmers' and agricultural scientists' curricula, as well as the public discourse. Both farmers and the society need to be aware of the connections between weed management, our food system and biodiversity. Perhaps weeds can then eventually be regarded as ecological goods produced by farmers, as suggested by Gerowitt et al. (2003a). The challenge, then, will be to test out practically viable weed management systems for the highest benefit of both biodiversity, society and farmers.

Further research is needed to explore such tools for farmers. For example, an important research area would be to test out weed management methods that maintain a diversity of weeds of higher ecological value while suppressing perennial weeds that are difficult to control. Necessary weed density levels for the needs of biodiversity could be evaluated for arthropods and birds. Largely unexplored is also the question of the value of specific arable weeds for small mammals. Also, attractive tools for crop management at a high degree of biodiversity should be tried out and researched for practical farming. Management suggestions that have previously been based on the economic weed density threshold should be revised and new thresholds should be developed based on both the ecological value, as well as the economic loss caused by weeds. To do this, more research will be needed to determine the ecological value of weeds in economic terms, as well. This should be done not only in the context of the individual field, but from a broader perspective of the agroecosystem or the whole biodiversity of Germany, for example.

These new, more sustainable approaches should be stipulated and supported by the German Federal Government according to the National Strategy for Sustainability and the Action Plan for the sustainable use of pesticides (Bundesregierung 2016; BMEL 2013). On the European level, they should be at the heart of the European Green Deal and the Biodiversity Strategy for 2030 whose aim it is, among others, to reduce the use of pesticides by 50% and to have 25% of total farmland under organic farming by 2030 (European Comission 2020).

Since farmers have to pay the price for such new, ecological weed management methods (for example due to lower yields), practical tools will be needed to fairly recompensate them for their efforts. After all, healthy environment and biodiversity are public goods. It is in the interest of the broader society to maintain them as healthy as possible and to ensure a sustainable use for future generations. As we have seen, farmers play a key role when it comes to maintaining biodiversity and the ecosystem services associated with agroecosystems. Public money should be spent on public goods provided by farmers. This will present another challenge for which further trials to develop and implement such financial instruments will be necessary (Gerowitt et al. 2003b). Finally, given the mounting evidence for the benefit of organic farming for biodiversity and other public goods (Sanders and Hess 2019), organic farming should be systematically encouraged and promoted.

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die hier vorliegende Arbeit „Common arable weeds in Germany support the biodiversity of arthropods and birds“ selbstständig und ohne Benutzung anderer als der angegebenen Quellen verfasst wurde.

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