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Responses of arable weeds to climate change

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1 Introduction

No other topic in science is currently discussed more than climate change, which has importance in almost any scientific field, including agricultural and natural sciences, but even political and sociological sciences. With regard to climate change, the scope of this thesis are arable ecosystems and weedy plants. Ecological, biological and agricultural aspects are covered and discussed in relation to each other.

Climate change will result in rising temperatures, different precipitation in the seasons, elevated levels of atmospheric CO_2 and extreme weather events, which are projected to occur more frequently and stronger (Patterson, 1995; Bloomfield et al., 2006; Lobell & Burke, 2008; Jentsch et al., 2009; Weigel, 2011; Ziska & Dukes, 2011; Coumou & Rahmstorf, 2012). These changes have profound impacts on crops, weeds, arable communities, cultivation, management methods and, as a whole, on arable ecosystems (Dukes et al., 2009; Singer et al., 2013). Weeds in arable ecosystems are either influenced directly by the altered conditions or indirectly by the enforced adaptations of management methods to changes in environmental conditions and altered biotic interactions within the community (Olesen & Bindi, 2002; Bloomfield et al., 2006; Walck et al., 2011; Ziska & Dukes, 2011).

Despite the enormous attention given to climate change in the last years, there are still knowledge gaps. For example, in agricultural research many studies analysed the effects of elevated CO_2, raised temperatures and drought stress on plants (Patterson, 1995; Morison & Lawlor, 1999; Fuhrer, 2003; Lobell & Burke, 2008; Ziska & Dukes, 2011). Yet, only few studies examined these factors combined (Patterson, 1995; Lavorel & Garnier, 2002; Weigel, 2011). In this context, most research is conducted under artificial conditions such as in greenhouses or in climate chambers. These results often are not in accord with responses of the species when growing under pure field conditions and with competition in plant communities (Poorter & Navas, 2003; Dukes, 2007). Experimentally, most studies assess parameters at early growth stages of plants, as this allows for results in a relatively short period of time. Generative parameters, such as seed production and biomass allocation at the end of the life of annual weeds, are rarely analysed with regard to altered climate conditions. Moreover, research is mainly directed toward agronomically important species such as crops, invasive and noxious weeds, rather than toward components of biodiversity such as rare and endangered weeds (Bergmann et al., 2010; Loss et al., 2011). Furthermore, ecosystematic effects of climate change are not well understood with regard to weeds, including population dynamics, functional connections of plant traits to climate and changes in species niches (Ohlemüller et al., 2006; Broennimann et al., 2007; Lososová et al., 2008; Nogués-Bravo, 2009).

This cumulative thesis closes some of these knowledge gaps and presents a comprehensive study on the effects of climate change on weeds in arable ecosystems. It is structured into three parts:

(1) A general introductory part that covers the theoretical background of climate change in arable ecosystems (see chapter 2, p. 5).

(2) The cumulative part that consists of four research papers including a review paper on shifts that occur at different scales (chapter 3, p. 49), a climate chamber experiment with agronomic important weeds in maize crop (chapter 4, p. 51), a semi-field experiment with these weeds (chapter 5, p. 53) and a semi-field study with rare weeds in wheat crop (chapter 6, p. 55). New methodologies for conducting experiments are established. The results perform as a basis for improving climate related modelling.

(3) A conclusive part, in which the results are discussed and evaluated comprehensively (chapter-spanning). Finally, an outlook is presented with regard to climate related weed modelling (chapter 7, p. 57).

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2 Background

2.1 Different types of crops and weeds

In arable ecosystems humans cultivate different types of crops and harvest them for food and for other uses. Since the beginning of agriculture crops are accompanied by weeds (Tab. 1, p. 8). In arable ecosystems, weeds do not appear randomly. Here, most weed species are typically linked with certain types of crops besides few generalist species that can grow over a wider range of crop types. As a result of long-term and short-term historical cultivation of crop, a characteristic weed species composition developed for certain types of crops in Central Europe. Weed related research often does not consider the processes involved with regard to the weed species composition. In the following, two different types of weeds and crops are distinguished.

2.1.1 Classic and modern crops

According to current knowledge, first crops were grown over 11,000 years ago (Vernet, 1990; Haak et al., 2010) in continental regions of Asia Minor, the Pontic-Caspian steppe and the Mediterranean area (Weinert, 1973; Jäger, 1977; Hüppe, 1987; Sutcliffe & Kay, 2000). Other unwanted plants always accompanied crops. As attachments to crops, these so called „weeds" were brought unconsciously along with the progression of agriculture to Central Europe (Tuexen, 1958; Weinert, 1973; Jäger, 1977; Hüppe, 1987; Sutcliffe & Kay, 2000) (Tab. 1, p. 8).

The domestication of classic crops, such as barley (*Hordeum vulgare*) and early wheat varieties (*Triticum* spp.), and the migration of accompanying weeds to Central Europe began in the Neolithic over 8,000 years ago (Guillerm et al., 1990; Robinson, 2010). Classic crops can be considered archaeophytic anthropochoric plants (Pysek et al., 2005), because they were slowly introduced after the last glacial period. The term „classic crops” includes, both, winter and spring cereals such as barley, wheat and rye (*Secale cereale*). About 41.24 Mio ha barley, rye, and wheat were cultivated in the European Union in 2010 (FAO, 2013).

In contrast to classic crops, „modern crops” were rapidly accepted by farmers and now are widely cultivated throughout Europe. Modern crops can be considered neophytic anthropochoric plants (Pysek et al., 2005), because they appeared just a few decades ago in Central Europe. They were introduced over a short period of time and over great geographical distances.

For example, oilseed rape formed around 2,000 years ago (Nagai & Sasaoka, 1929; U, 1935). In most parts of Europe it is cultivated for only about 200 years (Cramer, 1990; Kempken & Kempken, 2006). During the Second World War and especially in the 1970s when zero-eruca cultivars were bred and released, oilseed rape became the most important oilseed crop in Central Europe. About 7.07 Mio ha were cultivated in the E.U. in 2010 (FAO, 2013).

Another modern crop is maize, which was domesticated out of wild Teosinte species in Mexico over 9,000 years ago (Fukunaga et al., 2005). In Central Europe it is more widespread cultivated since the second half of the 20th century, when varieties were bred that had lower temperature requirements and allowed earlier ripeness compared to thermophilic cultivars (Carter et al., 1991; Kenny et al., 1993; Reilly et al., 2003). About 8.08 Mio ha were cultivated in the E.U. in 2010 (FAO, 2013).

2.1.2 Different weeds in different crops

In Central Europe, crops show substantial differences in the composition and abundance of weed species (Schroeder et al., 1993). The weed species composition is mainly affected by the grown crop besides edaphic factors, the season, altitude and climate (Andersson & Milberg, 1998; Hallgren et al., 1999; Lososová et al., 2004, 2006; Fried et al., 2008; Cimalová & Lososová, 2009; Silc et al., 2009; Gunton et al., 2011; Hanzlik & Gerowitt, 2011). Although ranking of these

Fig. 1: Different weeds are typically found in different crops. Left: Classic weed *Centaurea cyanus* in wheat crop. Right: Modern weed *Anchusa arvensis* in oilseed rape crop.

factors is inconsistent between the studies, the type of crop has been found to explain most of the variation in species composition (Gunton et al., 2011; Hanzlik & Gerowitt, 2011). The crop type also influences the interactions of weeds within the community (Swanton & Weise, 1991). Edaphic and climatic factors explain most of the other variance in the occurrences of weeds. Management methods, which are often distinctive for specific crops, are also known to influence weed occurrences (Hulme, 2008).

Thus, it is reasonable to differentiate the weed composition in classic crops (Behrendt, 1974; Neururer & Herwisch, 1976; Salonen et al., 2001) from the composition in modern crops (Behrendt, 1973; Mehrtens et al., 2005; Hanzlik & Gerowitt, 2012), although the overall weed species richness seems to be less distinguishable (Fried et al., 2008).

Tab. 1: Terminology is often used differently in the literature (Richardson et al., 2002). To avoid confusion, precise definitions of the types of arable weeds used in this thesis are provided here.

Type	**Description**	**References**
Weed	A plant that occurs on sites where it is not wanted. Arable weeds typically appear in arable ecosystems.	Rademacher (1948); Harlan & de Wet (1965); Richardson et al. (2002)
Indigenous	A plant that was present in an area or native to an area before the beginning of agriculture.	Pysek et al. (2002); Richardson et al. (2002)
Archaeophytic	Plants that were introduced before 1492 to Europe.	Kreh (1957); Quézel et al. (1990)
Neophytic	Species that joined the European flora after 1492.	Thellung (1912); Quézel et al. (1990)
Alien, Exotic, Newcomer	Plants that were recently introduced to the local flora.	Guillerm et al. (1990); Richardson & Pysek (2006)
Coloniser	Plants that are introduced to a non-native habitat and spread into other areas from that area.	Holzner & Immonen (1982); Carson (1987); Davis & Thompson (2000)
Invasive	Very competitive plants that may become a dominant plant in the ecosystem.	Guillerm et al. (1990)
Upstarter, „Chance species"	Some indigenous or archaeophytic weeds (which have already been present in the landscape) that just recently occurred in high abundances in arable ecosystems.	Baessler & Klotz (2006)
„*a priori*", pre-adapted, primary adapted	Weeds that possessed „weedy" properties before they appeared in crops.	Carson (1987); DiMichele et al. (1987); Baker (1965); Harlan & de Wet (1965); Liu et al. (2013)
„*a posteriori*"	Weeds that developed properties typical for weeds after they appeared in crops.	Thellung (1925); Hammer (1988)

2.1.3 Classic weeds

Fig. 2: Classic weed *Scandix pecten-veneris* in wheat crop.

Classic weeds, such as *Agrostemma githago*, *Centaurea cyanus*, *Papaver rhoeas*, *Bromus secalinus* and *Apera spica-venti* (Neururer & Herwisch, 1976; Hüppe & Hofmeister, 1990), are linked with classic crops since the beginning of agriculture (Tab. 2, p. 24). Classic weeds mainly originated in warmer, more continental regions in Asia Minor, the Pontic-Caspian steppe and the Mediterranean area (Weinert, 1973; Jäger, 1977; Hüppe, 1987; Sutcliffe & Kay, 2000). Human movements had caused range transformations of crops and weeds. Classic weeds have adapted to the slowly changing climatic conditions and cultivation methods over a long period of time. Even today, the ecologic and climatic conditions in cereal crops still resemble those of their natural habitat to a certain degree (Holzner & Immonen, 1982; Guillerm et al., 1990). Originally, most of these plants became weeds, because they already possessed a certain set of „weedy" properties, such as high seed output, annual life history and the ability to re-sprout (Baker, 1965). They can be described as pre-adapted, primary adapted or „*a priori*" weeds (Tab. 1), because they already possessed these properties before agriculture was practiced by humans (Harlan & de Wet, 1965; Carson, 1987; DiMichele et al., 1987; Liu et al., 2013). Darwin (1868) called this process „unconscious selection".

With the progression of cultivation, *a priori* weeds such as *Scandix pecten-veneris* among others migrated and adapted simultaneously with the crop (Kornas, 1990; Ellenberg, 1996) (Fig. 2). With the increasing distance to their native habitat they evolved further (Kleyer, 1999). Harlan & de Wet (1965) called this process secondary adaptation. Introgression of genes between weeds and crops and vice versa may have played an important part within their evolution (Harlan & de Wet, 1965). Humans also cropped some weeds. Some crops such as rye even developed out of weeds. Some weeds even became over-specialized and depended solely on the artificial conditions in crops, such as the meanwhile extinct linicolous weeds in flax *(Linum usitatissimum)* (Kornas, 1988; Hammer, 2003). The long cultivation history of classic crops is an important precursor for their current characteristic weed composition (Potts et al., 2010). For example, in Central Europe most weeds in classic crops are still archaeophytes (Tab. 1).

Classic weeds typically appear in classic crops in high species diversity (Lososová et al., 2004, 2006). Usually, the level of competition among them is high and many weed species form a diverse net of ecological linkages (Booth & Swanton, 2002). In classic crops many different weeds utilize resources very efficiently. As a result, they take up the free niche space very quickly and, thus, leaving little space for exotic and invading weed species (MacArthur, 1970; Maillet & Lopez-Garcia, 2000). Weeds that already are present in cereal crops also have a high level of regeneration (Lavorel & Garnier, 2002). Therefore, classic weeds can be characterized by a relatively high level of niche conservatism (Pearman et al., 2008). Most weeds in cereals are trying to retain their properties, because they have adapted to the small changing conditions in cereal management over the centuries (Svensson & Wigren, 1986a).

Most classic weeds belong to the phytosociological class Secalinetea. This class was not present in prehistoric times and has evolved with the three-field system during the Middle Ages and with the migration of weeds to Central Europe (Oberdorfer, 1983; Hilbig, 1987; Sukopp et al., 1994; Küster, 1995). The species composition in classic crops was never fixed. The three-field system and fallow periods between crop rotations led to rich species composition until approx. 150

years ago (Eggers, 1984). With the conversion of cropping systems and the introduction of sophisticated seed cleaning methods some weeds became rare that allow easy seed cleaning, such as *Agrostemma githago* and *Scandix pecten-veneris*. The reduction in species richness continued with the introduction of sophisticated mechanical weed control mechanisms (Holzner, 1984; Eggers, 1984; Meisel, 1985; Kornas, 1988). Interestingly, the total number of arable weed species increased slightly after a period of reduction during the past 25 years (Baessler & Klotz, 2006). This is mainly due to the loss of archaeophytes and the gain of neophytes and upstarters (Svensson & Wigren, 1983; Potts et al., 2010) (Tab. 1). Classic weeds with obsolete traits are more and more replaced by those favored by modern methods (Storkey et al., 2010). The increasing agricultural uniformity also favors generalist species instead of former habitat specialists (Albrecht, 1989; Baessler & Klotz, 2006). As a result, the number of arable newcomers in cereals is higher today than it was approx. 150 years ago (Behrendt, 1974; Guillerm et al., 1990) (Tab. 2, p. 24).

2.1.4 Modern weeds

Modern weeds are weeds that are typically found in modern crops. Most of them are neophytes and were introduced after 1492. In order to persist they need to develop or optimize certain of their properties. Modern weeds can also be described as „a posteriori" weeds (Tab. 1), because they appeared in the crop after its introduction (Thellung, 1925; Hammer, 1988).

Most modern weeds belong into the phytosociological class Chenopodietea, which mainly include species for nutrient-rich and disturbed habitats (Tuexen, 1958; Holzner & Immonen, 1982; Ellenberg, 1996). This mainly includes indigenous, neophytic, exotic and alien species (Tab. 1). Exotics were introduced over long geographic distances. For example, *Amaranthus retroflexus*, *Ambrosia artemisiifolia* and *Datura stramonium* have been introduced from North America and Mexico to Central Europe (Fig. 3). Some of these exotic weeds tend to have properties that we call invasive nowadays (Baker, 1974; Sakai et al., 2001; Sutherland, 2004; Pysek & Richardson, 2007; Dukes et al., 2009; Clements & Ditommaso, 2011). In an ongoing debate it is argued that the old archaeophytic weeds in classic crops once have been invasive too (Bunting, 1960; Ellenberg, 1996; Barrett, 2000). Evolutionary, modern crops harbor younger and less specialized weeds when compared to most weeds found in classic crops (Pysek et al., 2005; Hobbs, 2000). Many modern weeds are also adapted to a wider range of climatic conditions and to relatively high degree of ecological disturbance and abiotic fluctuations (Rejmanek, 1989; Huston, 1994; Levine & D'Antonio, 1999).

Recently, modern agricultural methods have facilitated the spread of upstarters into arable ecosystems (Lohmeyer, 1954; de Wet, 1966; Holzner, 1984; Baessler & Klotz, 2006) (Tab. 1, 2). As such, *Solanum nigrum*, *Chenopodium album* and *Stellaria media* also found favorable conditions outside of their natural habitat (Ellenberg, 1996; Holzner & Immonen, 1982). Originally, these species were restricted to relative small areas along rivers and lived in generally opened and disturbed sites (Krause, 1956). Yet, these species are indigenous to Central Europe and were present even before agriculture was practiced by humans (Baker, 1965) (Tab. 1). Today, these upstarters are actively extending their range into arable ecosystems by modifying or developing opportunistic properties – which is characteristic for modern weeds (Lososová et al., 2008).

Fig. 3: Modern weed *Amaranthus retroflexus* in maize crop.

Nevertheless, boundaries overlap with the distinction of modern and classic weeds, as e.g. nowadays *Stellaria media* is also found in great abundances in, both, winter cereals and oilseed rape. Processes involved with the distinction of classic and modern weeds are similar to those found in plant sociology. Here, in plant communities there can be distinguished characteristic species from differential and accompanying species (Braun-Blanquet, 1964; Wilmanns, 2002; Ellenberg, 2009). As weeds have numerous interactions and ecological linkages, further determination of characteristic weeds in crops can help to understand the processes involved with the establishment of weeds, the formation of weed communities and the functional connections between weeds and crops (Ellenberg, 2009; Petit et al., 2011).

2.2 Climate change

In this thesis the term „climate change" is used by means of variations in the climate.

There are natural causes of climate change. For example, the periodically occurring variations in the earth's orbit around the sun (the Milankovitch cycles) (Hays et al., 1976; Wunsch, 2004; Roe, 2006), natural variations in the ocean surface temperature, namely „El Niño" and „La Niña" (Thompson et al., 2010), changes in the composition of tropospheric aerosols due to e.g. volcanism (Mann et al., 2009) and solar cycles and associated magnetic field variations of the earth and the resulting changes in the formation of clouds (Lassen & Friis-Christensen, 1995; Svensmark, 2012; Schurer et al., 2014; Sherwood et al., 2013).

Most natural climatic changes occur periodically in cycles. This leads to alternating warm and cold periods: the thermohaline circulation (Marcott et al., 2013). The current period termed „Holocene" is a period of warming of natural causes. The Holocene began after the last glacial period approx. 11,700 years ago. The current natural process of warming is caused by the elliptical orbit of the earth around the sun and a decrease in the distance to the sun by the other planets, which reaches every 100,000 years its turning point (Wunsch, 2004; Roe, 2006).

However, natural climate change is exceedingly superimposed by an anthropogenic warming of the Earth's atmosphere, which is termed „global warming" or „greenhouse effect". This significant anthropogenic warming is caused by the emission of several greenhouse gases such as CO_2, N_2O, CH_4, H_2O, among others (Patterson, 1995). Currently, anthropogenic urban heat islands are discussed to warm the global climate as well (Zhang et al., 2013).

2.2.1 Climate change in Europe

The climate in Europe was variable within the last 1,500 years (Mann et al., 2009). For example, temperatures during the Medieval warming period (approx. 950–1,250 A.D.) were almost +2.5°C above the temperatures measured in the reference period 1961–1990. Subsequently, a period of cooling followed, termed „Little Ice Age", where temperatures were approx. -1.0°C below the reference period (Mann et al., 2009).

Current climate projections predict a temperature increase which exceeds natural temperature anomalies considerably by the end of this century (Bradley et al., 1999; Tubiello et al., 2007; Gillett et al., 2011). Based on the A1B (RCP6.0) scenario of the IPCC, for Europe an increase in temperatures of approx. +3°C is predicted by the end of this century (IPCC, 2013). The temperature increase is projected to be different in the seasons resulting in a higher temperature increase during winter than during summer (Bloomfield et al., 2006; Bergmann et al., 2010).

Over the last ten to fifteen years a slight mitigation in the increase of air surface temperatures has been determined, which was not predicted by most climate projections (IPCC, 2013). This mitigation is most likely caused by various factors such as the extraordinarily high temperature conditions in the arctic in the last years (Screen, 2013; IPCC, 2013; Pistone et al., 2014), the „La Niña" oscillation of cold ocean water which was more pronounced and the natural periodic decline in the sun's activity (Kosaka & Xie, 2013). Even the reduction in greenhouse gases such as CFC and methane may contributed to a minor reduction in air surface temperatures (Estrada et al., 2013; IPCC, 2013). Contrarily to the aforementioned reductions, over the last ten years the sea surface temperatures increased according to predictions (Kosaka & Xie, 2013). However, those short-term variations in weather should not be confused with long-term climatic developments, which are modelled by climate projections. Additionally, the smaller the temporal scale the more variable the climate and, thus, variations in local climate conditions. For example, the surface temperature in Austria increased more during the last 100 years than in other countries in Europe (APCC, 2014). This exacerbates accurate climate projections for particular regions. Since only approx. 84% of the surface area of the earth are covered with measuring stations, the level of warming could even have been underestimated as a result of extrapolation (Cowtan & Way, 2013; IPCC, 2013).

Precipitation and humidity are predicted to fluctuate strongly with climate change at both regional and temporal scales (IPCC, 2013). Currently, there are efforts to increase the model accuracy. According to Marvel & Bonfils (2013), precipitation declines in dry regions and increases in humid regions with climate change. Additionally, the circulation of the precipitation amount shifts poleward similarly to the poleward shifting of temperatures. Thus, in Central Europe future summers are predicted to get drier and winters are predicted to get wetter (Bloomfield et al., 2006; Lobell & Burke, 2008; Robinson & Gross, 2010). A northeast shift in analogous climates across Europe is also predicted (Bergmann et al., 2010).

The kinetic energy of atmospheric particles is directly correlated to temperature. As a consequence, extreme weather events such as heavy storms, heavy rains, prolonged summer droughts and extreme winter cold spells occur more frequently and likely stronger with climate change (Allen-Diaz et al., 1996; Díaz et al., 1999; Sala et al., 2000; Walther et al., 2002; Tubiello et al., 2007; Jentsch et al., 2009; Coumou & Rahmstorf, 2012).

2.3 Direct effects of climate change

In arable ecosystems, increases in the surface temperature, changes in the precipitation and extreme weather events have strong impacts on crops, weeds and pests (Patterson, 1995; Bloomfield et al., 2006; Williams, 2009; Weigel, 2011; Juroszek & von Tiedemann, 2013). As a result, agriculture and agronomy are under more pressure due a more challenging weed control and potentially lower yield. In the following sections, the outcome of climate change on weeds and crops are explained in more detail.

Weeds respond to the potentially stressful altered conditions which result from climate change (Dukes et al., 2009; Singer et al., 2013). For example, the survival of some winter annual weeds is directly affected by the predicted wetter and milder winters. Similarly, longer growing seasons may permit thermophile summer annuals to grow in regions further to the north (Bloomfield et al., 2006; Walck et al., 2011; Hanzlik & Gerowitt, 2012). Extreme weather events and rapid climatic changes have direct ecosystematic effects. It is likely that both processes increase the level of disturbance and further disrupt the stability of arable ecosystems (Dukes & Mooney, 1999).

The effect of increased levels of atmospheric CO_2 has been studied intensively for some plants (Zangerl & Bazzaz, 1984; Patterson, 1995; Ziska, 2003b; Rogers et al., 2008; Weigel & Manderscheid, 2012; Manderscheid et al., 2014). Although there are few studies that explore direct effects of atmospheric CO_2 enhancement on weeds, for arable weeds can be concluded that the proportion of C_4 weeds such as *Amaranthus retroflexus* or wild millet weeds, such as *Echinochloa crus-galli*, *Setaria* spp. and *Digitaria* spp., is likely to increase with climate change, as these species are predicted to migrate from warmer regions to locations further north (Weber & Gut, 2005; Walther et al., 2002). Despite that elevated levels of CO_2 can reduce drought stress for some C_3 crops (Manderscheid & Weigel, 2007), the proportion of summer annual C_3 weeds is still projected to decrease due to higher transpiration rates when compared to C_4 weeds with the predicted drier conditions during summer (Morison & Lawlor, 1999; Ziska, 2003a).

Over the last 50 years, a change in the phenology of plants has been determined and this change is often referred to as a fingerprint of climate change (McIntyre et al., 1999; Root et al., 2003; Jentsch et al., 2009; Thackeray et al., 2010; Gunton et al., 2011). As a consequence, the onset of flowering of wild cherries (*Prunus avium*) in spring has occurred 0.13 days per year earlier and the begin of leaf coloring of horse-chestnut (*Aesculus hippocastanum*) in autumn has occurred 0.25 days per year later on the average (Menzel et al., 2003). Thus, the vegetation period was approx. 24 days longer in the year 2000 when compared to 1951 (Menzel, 2003; Menzel et al., 2003; Chmielewski et al., 2005).

Important outcomes of altered phenology are alterations in the sowing and harvesting dates of crops. They advanced approx. 1.1 to 1.3 days per decade in Germany, whereas in some regions of France the time of sowing advanced almost a month between 1951 and 2000 (Estrella et al., 2007). Phenology is also important for weeds, as most species have adapted their germination timing and development speed according to the crop (Otte, 1990; Otte et al., 2006; Parmesan, 2006). If the germination period of the weeds is located outside of the crop sowing period, the weed will most likely vanish (Otte, 1990; Otte et al., 2006). Phenology has also effects on the physiology and the evolution of weeds (Swanton et al., 1999; Franks et al., 2007; Franks & Weis, 2008). Longer growing seasons enable some species to grow further to the north and successfully reproduce in regions, where it was not possible for them to produce seeds before the beginning of winter, as it has been described for *Abutilon theophrasti* (Andersen et al., 1985; Warwick & Black, 1986; Ghersa & Holt, 1994; Westerman et al., 2012). Finally, changes in phenology also affect animals, fungi and pollinators (Fitter & Fitter, 2002; Root et al., 2003; Thackeray et al., 2010).

2.4 Indirect effects of climate change

Arable ecosystem are strongly influenced by human actions and are shaped by seasonal disturbances such as sowing, harvesting, pesticide usage, tilling, and crop rotations (Rademacher, 1948; Harlan & de Wet, 1965). The composition of arable weeds is greatly affected by these agricultural methods (Grime, 1977; Grime & Hodgson, 1987; Chapin et al., 1996; Sutherst, 2000; Klotz & Kühn, 2002; Smith, 2006). As methods and land use have to be adapted to the changing conditions in order to maintain yield and the same level of weed control, environmental changes, such as increases in the surface temperature, prolonged droughts and other extreme weather events, can exert great impact on weeds (Patterson, 1995; Bloomfield et al., 2006; Williams, 2009). Thus, in research it is often argued that indirect effects of climate change can have greater impact on the arable weed flora than direct effects (Glemnitz et al., 2006). In the following, these indirect effects are explored with regard to weeds and crops.

2.4.1 Crops and climate change

In Europe, rising surface temperatures facilitate the cultivation of crops such as maize further to the north (Walther et al., 2002, 2009) despite that the recent shift of maize cultivation to Scandinavia occurred mainly due to breeding efforts (Barrett, 2000; Estrella et al., 2009). With rising temperatures, the number of crops may increase for some regions of Europe, as new crops are introduced that formerly did not find suitable conditions. For Germany it is projected that farmers are more likely to cultivate sunflower (*Helianthus annuus*), soybean (*Glycine max*) and peach (*Prunus persica*) with climate change (Bloomfield et al., 2006).

Higher atmospheric levels of CO_2 can be beneficial for the growth of crops (Weigel & Manderscheid, 2012; Manderscheid et al., 2014). However, the CO_2 enhancement effect shrinks when temperatures and nutrient availability are accounted for (Rosenzweig et al., 2013). With rising temperatures, nitrogen stress and water scarcity will increase for plants (Rosenzweig et al., 2013). The effect is more distinctive in low-latitude regions (Schewe et al., 2013) and, thus, a decline in yield is predicted for wheat, maize, soybean and rice in these regions (Rosenzweig et al., 2013). As a result, food production and food security will also be affected indirectly by climate change (Weigel, 2011; Rosenzweig et al., 2013).

Climate change also influences breeding of crops and the choice of cultivars. For example, predicted future conditions influence the choice toward summer annual cultivars that germinate earlier in the season and toward winter annual cultivars that germinate later in the season. Breeding efforts are directed toward cultivars that are more tolerant toward drought stress and develop higher biomass under high atmospheric levels of CO_2 (Olesen & Bindi, 2002; Weigel, 2011). Since food production is projected to be under higher pressure, old crops such as buckwheat (*Fagopyrum esculentum*) and spelt (dinkel wheat, *Triticum spelta*) are even less and less cultivated (Olesen & Bindi, 2002). As a result, the conservation of old crops will be more challenging under climate change and, thus, also the conservation of associated rare weed species (Kühn, 1994).

2.4.2 Management and land use under climate change

Most management methods are designed to remove interfering species. This results in lower interspecific competition between weeds and the crop (Aerts, 1999) and, thus, in further degradation of the ecosystem (Watson et al., 2000; Urban, 2003). Due to the predicted higher pressures on yield, it is predicted that with climate change pesticide usage or doses will be increased, management methods get more intensive and cover also less fertile soils (Barrett, 2000). As a result, ecologic and genetic diversity is reduced further, which can be an opportunity for invasive weeds (Smith et al., 1999). In such a strongly shaped ecosystem, extreme weather events also exert greater impact due to the uniformity of the landscape (Walther et al., 2002).

For climate change conditions, studies analyzed pesticide usage and efficiency regarding altered temperatures, altered run-off due to different precipitation, altered susceptibility and resistance in weeds to herbicides and physiologic effects of herbicides in weeds (Barrett, 2000; Clements et al., 1994; Bloomfield et al., 2006). Only few studies analyzed the abiotic and biotic degradation of herbicides. Herbicide resistance in weeds is also linked to the degradation of herbicides and could be affected by climate change as well (Bloomfield et al., 2006), since higher temperatures can accelerate the catabolism of herbicides in plants (Ziska et al., 1999; Barrett, 2000; Bunce & Ziska, 2000; Ziska, 2000). Possible hybridizations between weeds and crops have been rarely considered with climate change (Ellstrand & Hoffman, 1990; Barrett et al., 2008).

Land use will also be adapted to climate change. It is projected that agriculture is expanded to low-yield sites, which will augment the uniformity of the landscape even more (Barrett, 2000; Rosenzweig & Hillel, 2000; Baessler & Klotz, 2006; Lososová et al., 2006). A more uniform landscape facilitates the dispersal of small weed seeds. Profiting species are generalists concerning a homogeneous nutrient availability (Bunting, 1960; Baker, 1965; Saunders et al., 1991) and weed species that possess sophisticated dispersal mechanisms under these conditions (Barrett et al., 2008). It is projected that exotic and invasive species benefit more than other species from a more uniform landscape due to their sophisticated dispersal (Saunders et al., 1991).

2.5 Conservation of weeds under climate change

Approx 70% of the area of Germany is cultivated (Hilbig & Bachthaler, 1992a) – the bigger part of this area is cropped intensively. Conservation is mainly restricted to a minimum within legal policies. The intensive cultivation of arable land mainly results in the loss of specialist species and a gain of generalist species, including invasives (Holzner & Immonen, 1982; Robinson & Sutherland, 2002; Pysek et al., 2005; Neve et al., 2009; Fried et al., 2010). Climate change is projected to facilitate the loss of diversity and, thus, a reduction of associated birds, insects and other organisms (Marshall et al., 2003; Storkey, 2006; Fried et al., 2009).

Indirect effects of climate change, such as the run-off of pesticides and erosion due to extreme weather events, are projected to occur more often and with increased intensity (Howden et al., 2007; Schaller & Weigel, 2007). By creating niche gaps that can act as gateways for invasives, erosion directly affects weed populations (Saunders et al., 1991; Vitousek et al., 1997; Barrett, 2000; Storkey et al., 2010; Sutherst, 2000). Climate change also leads to an increased nutrient run-off, which affects species in nearby habitats and species that possess traits related to low nutrient availability in the soil (Kreyling et al., 2009). Both, erosion and run-off can also influence neighbouring ecosystems. The expansion of arable intensification to less profitable locations may further remove refuges for rare species (Marshall et al., 2003) and, thus, result in higher fragmentation of special sites (Singer et al., 2013).

In research there is an ongoing dispute, whether conservation in arable ecosystems (which are nevertheless shaped by human interferences) is reasonable. However, with climate change, a preservation of arable diversity has more benefits rather than disadvantages. For example, some non-intrusive weeds reduce erosion due to deep rooting (Hilbig & Bachthaler, 1992b). A diverse arable species composition can prevent exotic or invasive species to establish in the community (Elton, 1958; MacArthur, 1970; Cardina et al., 2002; Pautasso et al., 2010; Singer et al., 2013) – despite some critics with this concept (Levine & D'Antonio, 1999; Levine, 2000). Weeds are also known to control some crop diseases (Van Elsen & Scheller, 1994; Clements et al., 2004). By contrast, genetically related weeds may also act as vector for diseases, whose spread is also affected by changing climatic conditions (Patterson, 1995; Juroszek & von Tiedemann, 2013).

In addition to rarity among weeds, it is still uncommon for conservation to explore their 'option value'. For example, the classic weed *Scandix pecten-veneris* (Fig. 2, p. 9) is being used as a traditional vegetable in some parts of the

Mediterranean (Liopa-Tsakalidi, 2014). Leaves can be used as salad and young fruits are edible when cooked or boiled. Conservation of wild populations is also reasonable from a health standpoint, as plants are reported to be sources of antioxidants and ω-3 fatty acids (Liopa-Tsakalidi, 2014). Besides that the option value of many rare weeds has not been explored, local traditions have been forgotten with the introduction of intensive agriculture. So far, the influence of climate change on the concentration of certain chemical components has only been explored for some abundant weeds with regard to photosynthesis and other chemical pathways (Morison & Lawlor, 1999; Urban, 2003; Ziska & Dukes, 2011).

Most rare weeds have low phenotypic plasticity and possess certain characteristic trait syndromes, e.g. nutrient retention and large seeds (Baker, 1965, 1974; Storkey, 2006). As a result, they often are adapted to very specific habitat conditions and, hence, are considered specialists. Highly specialised species often have extraordinary genetic evolution (Franks & Weis, 2008). Since rarity among specialists is often linked to fragmentation and geographic isolation, this frequently leads to genetic drift and outbreeding depression (Barrett & Kohn, 1991; Fenster & Dudash, 1994; Fried et al., 2010). If climate change occurs too rapidly, specialist species may not be able to track environmental changes (Bloomfield et al., 2006; Jump et al., 2008; Clements & Ditommaso, 2011).

There are very few studies on arable weeds with regard to climate change (Bergmann et al., 2010). Most often rare species are studied with regard to indirect effects such as changing management practices (Loss et al., 2011). Studying rare weeds and their response to altered conditions is vital for determining the direct effects of climate change (Dukes & Mooney, 1999). For instance, as a result from low phenotypic plasticity rare weeds may not be competitive under future climate conditions. In order to prevent local extinction, additional conservation measures may be needed, such as managed relocation or assisted colonization (Richardson et al., 2009; Loss et al., 2011). The requisites for these measures can only be determined with climate related experiments and modelling approaches. For an accurate modelling, long-term observations are needed (Dukes & Mooney, 1999).

Research should also further focus on plant communities, since rare weeds are often accompanied by other rare species (Moonen & Bàrberi, 2008).

Conservation measures that were introduced in the 1990s, such as small-scale extensive cropping, extensive buffer strips along field edges and the promotion of fallows (Hilbig & Bachthaler, 1992b; Küster, 1994; Schneider et al., 1994), seem to be less promising for weeds with regard to climate change (Marshall et al., 2003). Since the dispersal capabilities of rare weeds are often limited due to rare trait syndromes, migration of rare species is only successful if buffer strips are connected with each other in the landscape (Storkey, 2006; Svensson & Wigren, 1986b). Indeed, most often, buffer strips are fragmented in the landscape. With climate change and the proposed loss of climatically suitable habitats for rare species (Pompe et al., 2011), the long-term success of buffer strips is most likely very limited (Loarie et al., 2009). To prevent further biodiversity loss in arable ecosystems with climate change, promising measures include diversification of management practices, more functional crop rotations, no till and mulch seeding methods, intercropping and conservation of resources (Marshall et al., 2003; Holland, 2004). Some organic farming systems are known to provide these measures. Moreover, they are expected to be less vulnerable to climatic fluctuations and require fewer emissions of greenhouse gases (Fritsche & Eberle, 2007; Albrecht & Engel, 2009; FAO, 2013). Policy should accomplish to create agricultural areas similar to nature reserves that undergo special legislative protection and provide traditional farming methods and human encouraged dispersal in order to create suitable habitats for rare weed species (Svensson & Wigren, 1986b).

2.6 Climate change affects classic and modern weeds differently

As analyses from plant sociology and statistics demonstrate, the abundance and composition of weeds is different in classic and modern crops (Tuexen, 1950; Hüppe & Hofmeister, 1990; Fried et al., 2010, see also section 2.1.2). Although all weed species are equally filtered by the climate, the environment and the ecosystem each species is differently affected by the climatic alterations, because the response of each weed occurs within its characteristic phenotypic plasticity (Baker, 1965; Pearman et al., 2008; Matesanz et al., 2010). Climate change will most likely favor species that already possess or are able to develop opportunistic properties. When compared to classic weeds, modern weeds, such as *Abutilon theophrasti*, *Amaranthus retroflexus*, *Ambrosia artemisiifolia*, *Datura stramonium*, *Digitaria* spp., *Geranium* spp., *Panicum dichotomiflorum* and *Sorghum halepense* (Tab. 2), possess more traits related to drought and heat tolerance, high seed production, small seed size and light seed weight that are beneficial under predicted future conditions (Brandes, 1995; Hulme, 2008).

Currently, in Central Europe, most of the weeds found in modern crops (Tab. 2) are at the northern border of their distribution range. Since evolutionary drifts and migration rates are higher at the distribution borders, the adaptation capability of modern weeds is likely higher (Davis & Shaw, 2001). Thus, modern weeds are often better suited to track rapid climatic changes and climate change will most likely have stronger effects on the weed vegetation of modern crops (Davis & Shaw, 2001; Bloomfield et al., 2006; Jump et al., 2008; Clements & Ditommaso, 2011).

Currently, in classic crops, weeds have been adapted to various management practices. They still form relatively stable communities and many species prevent the establishment of arable newcomers such as exotic and invasive species (Booth & Swanton, 2002). On a long-term basis, climate change leads to an attenuation of ecological linkages between the weeds (Svensson & Wigren, 1983). Thus, invasive species may establish themselves more easily, which yet are mostly unknown for classic crops in Central Europe (Hyvönen et al., 2011; Stratonovich et al., 2012). Classic weeds, such as *Apera spica-venti*, *Alopecurus myosuroides* and *Avena fatua*, that posses properties similar to the crop, are the outcome of long-term evolutionary processes such as adaptation and co-evolution (Holzner &

Tab. 2: Examples of weeds possessing either classic or modern properties. Some archaeophytic weeds such as *E. crus-galli* and *S. italica* were in cultivation before and migrated along agriculture, but they evolved properties typically for modern weeds after their introduction in crops. Symbols used: ↑ = predicted climate conditions may profit the species; ↓ = the predicted climate conditions may be disadvantageous for the species; ∧ = upstarters; **Bold font** mark weeds on which experiments were conducted as part of this thesis.

Classic weeds	**Modern weeds**
Adonis annua	*Abutilon theophrasti* ↑
Agrostemma githago	***Amaranthus retroflexus*** ↑
Alopecurus myosuroides	*Ambrosia artemisiifolia*
Apera spica-venti ∧	*Anchusa arvensis*∧
Aphanes arvensis	*Chenopodium album* ↑∧
Arnoseris minima	*Datura stramonium* ↑
Avena fatua	*Descurainia sophia* ↑
Bromus secalinus	*Digitaria* spp. ↑
Bromus tectorum	***Echinochloa crus-galli*** ↑
Centaurea cyanus ↑∧	*Galium aparine* ∧
Chrysanthemum segetum	*Geranium* spp. ↑∧
Echinochloa crus-galli ↑	*Panicum dichotomiflorum* ↑
Lithospermum arvense ↑	*Poa annua* ↑∧
Matricaria recutita	***Setaria viridis*** ↑
Papaver rhoeas	*Sisymbrium* spp. ∧
Ranunculus arvensis	*Solanum* spp. ∧
Scandix pecten-veneris ↓	*Sorghum halepense* ↑
Setaria italica	*Stellaria media* ↑∧
Veronica polita	*Xanthium strumarium*

Immonen, 1982; Clements et al., 1994) (Tab. 2). By contrast, similar weeds, such as *Sisymbrium* species, *Descurainia sophia* and *Capsella bursa-pastoris*, found in oilseed rape and *Setaria* spp. and *Digitaria* spp. found in maize are the outcome of short-term selection processes mainly caused by intensive management (Fried & Reboud, 2007) (Tab. 2). Thus, similar to the way how climate change affects management, weeds are influenced by the selection processes of climatic changes.

2.7 Climate change affects plants at different scales

In the preceding sections, the various effects of climate change on weeds and crops were explored. Indeed, climate change affects plants at different scales (Tab. 3). Biological responses of plants explain the effects of climatic changes at the population scale, whereas ecosystematic effects become more apparent at spatially larger scales (Leibold et al., 2004; Powell et al., 2013). At the landscape scale, the effects of climate change on weeds are well understood (Cimalová & Lososová, 2009; Silc et al., 2009; Walck et al., 2011) (Tab. 3). Currently, research aims at modelling range shifts geographically with the help of parameters related to future climate conditions, soil and agriculture. These parameters often are also linked to species niches or to community processes (Lavorel et al., 1999; Broennimann et al., 2007; Ebeling et al., 2008; Auffret et al., 2010; Bergmann et al., 2010). The morphologic scale as part of the population scale is moderately studied with regard to climate change (Tab. 3). Most studies either focus on the traits of weeds during emergence and early growth, or, in this context, they focus on noxious and invasive weeds (Maillet & Lopez-Garcia, 2000; Smith, 2006; Lososová & Simonová, 2008; Jauni & Hyvönen, 2012) (Tab. 1, p. 8). At the physiologic scale there are many studies on the responses of weeds to elevated CO_2 (Zangerl & Bazzaz, 1984; Morison & Lawlor, 1999; Ziska et al., 1999; Ziska, 2003a; Rogers et al., 2008) (Tab. 3). Processes linking climate change at the genetic scale are difficult to study, as short-term climate processes are not immediately observable in the different expression of genes (Franks & Weis, 2008) (Tab. 3).

To conclude, there is still uncertainty among the scientific community on how to integrate the findings at distinct scales with each other (Leibold et al., 2004; Guisan & Thuiller, 2005; Kraft et al., 2011; Powell et al., 2013).

Tab. 3: Climate change affects plants at different scales.

Scales	**Sub-scales**	**Important mechanisms and consequences of climate change**
Population scale	Genetic scale	Evolutionary adjustments of the species to different climate conditions may result in genetic alterations over several generations (Franks & Weis, 2008).
	Physiologic scale	Alterations in metabolic or catabolic pathways. For example, higher temperatures can accelerate the degradation of metabolites such as herbicides (Patterson et al., 1999; Ziska et al., 1999). Elevated levels of atmospheric CO_2 can improve carbon fixation in some C_3 plants (Czerniakowski et al., 2006) and can slow the rate of transpiration in some C_4 plants (Morison & Lawlor, 1999; Ziska, 2003a).
	Morphologic scale	Alterations of traits and other morphological adaptations of plants within their phenotypic plasticity (Franks & Weis, 2008). For example, altered temperatures, different soil humidity and elevated levels of CO_2 can influence the germination, the emergence, the flowering duration, the biomass and the seed production of weeds (Patterson et al., 1999). (Refer also the review paper on „trait shifts" on page 49; The experiments conducted as part of this thesis also cover this scale, see chapters 4, 5 and 6.)
Community scale		Alterations in species niches due to climatic changes and adaptations of agricultural methods. This results in a different composition of arable weeds (Weiher et al., 1999). (Refer also the review paper on „niche shifts" on page 49.)
Landscape scale (Meta-community scale)		Alterations in species distributions (movement of range boundaries poleward) (Walther et al., 2002; Jump et al., 2008). (Refer also the review paper on „range shifts" on page 49.) In ecology, this scale is also known as meta-community scale (Leibold et al., 2004).

2.8 Research questions

The main objective of this cumulative thesis is to explore the responses of arable weeds to climate change. To this objective, a review paper was written to cover underlying mechanisms and ecological consequences of the responses of weeds to climate change at different scales (chapter 3, p. 49). Another main objective is to study the responses of arable weeds at the morphologic population scale (Tab. 3). To this end, two experiments were conducted with three modern weeds in maize crop: *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria viridis* (chapter 4, p. 51 and chapter 5, p. 53). Moreover, one semi-field experiment was conducted with the rare weeds *Lithospermum arvense* and *Scandix pecten-veneris* in classic wheat crop (chapter 6, p. 55).

The key research questions for this thesis are: What are the underlying mechanisms and ecological consequences of climate change for arable weeds at the different scales? What methodology can be used to study the effects of climate change on arable weeds? Which biological responses realize weeds in order to cope with a temperature increase of 2°C, changes in humidity and changes in the emergence period? How respond weeds to indirect effects such as altered crop densities? Which implications can be drawn from the weed's responses for agriculture and conservation? Are biological responses at morphological population scale, such as in the seed production of weeds to altered conditions, also important at spatially larger scales? How and in which way can the experimental results help to further improve modelling?

These questions are approached in the cumulative part of this thesis as found in chapters 3 – 6. Finally, a chapter-spanning synthesis is accomplished in chapter 7.

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3 Impact of climate change on weeds in agriculture: a review

Kristian Peters, Laura Breitsameter & Bärbel Gerowitt

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[1] http://link.springer.com/article/10.1007%2Fs13593-014-0245-2

Abstract

Over the past decades, climate change has induced transformations in the weed flora of arable ecosystems in Europe. For instance, thermophile weeds, late-emerging weeds, and some opportunistic weeds have become more abundant in some cropping systems. The composition of arable weed species is indeed ruled by environmental conditions such as temperature and precipitation. Climate change also influences weeds indirectly by enforcing adaptations of agronomic practice. We therefore need more accurate estimations of the damage potential of arable weeds to develop effective weed control strategies while maintaining crop yield. Here we review the mechanisms of responses of arable weeds to the direct and indirect effects of climate change. Climate change effects are categorized into three distinct types of shifts occurring at different scales: (1) range shifts at the landscape scale, (2) niche shifts at the community scale, and (3) trait shifts of individual species at the population scale. Our main conclusions are changes in the species composition and new species introductions are favored, which facilitate major ecological and agronomical implications. Current research mainly considers processes at the landscape scale. Processes at the population and community scales have prevalent importance to devise sustainable management strategies. Trait-climate and niche-climate relationships warrant closer consideration when modeling the possible future distribution and damage potential of weeds with climate change.

4 Important maize weeds profit in growth and reproduction from climate change conditions represented by higher temperatures and reduced humidity

Kristian Peters & Bärbel Gerowitt

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[2] http://pub.jki.bund.de/index.php/JABFQ/article/view/3044

Abstract

Climate change is predicted to result in rising temperatures and reduced precipitation during spring and summer in Central Europe. As a consequence, crops and weeds will be affected. Our study focuses on the three weed species in maize *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria viridis*. These weeds occur numerously in European maize fields and populations are likely to further increase. Yet, there is a lack of knowledge about particular biological strategies of the weeds. Our study focuses on how the weed species respond biologically to the climate change conditions. Experiments were conducted in two climate chambers with a 2°C difference in temperature and the warmer one with 13% less humidity. Emergence, development, biomass and seed production were determined of the weeds grown individually in pots and grown within maize. All tested weed species were taller during the first weeks under the climate change scenario. At later growth phases there was a trade-off between traits measured during vegetative growth and at the time when seeds were produced. To summarize the results, the weed species profited in the order *E. crus-galli*, *S. viridis* and *A. retroflexus* from the climate change conditions. Knowledge of the weeds biological responses to the predicted conditions helps to reduce their long-term population development by targeting crop protection measures at specific growth phases of the weeds. To ensure control of the tested weed species under climate change conditions various weed management strategies are necessary.

5 Weed growth properties of *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria viridis* as influenced by shifts in the maize cropping season

Kristian Peters & Bärbel Gerowitt

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[3] http://www.jpdp-online.com/Weed-growth-properties-of-iAmaranthus-retroflexusi-iEchinochloa-crus-gallii-and-iSetaria-viridisi-as-influenced-by-shifts-in-,QUlEPTQ2Nzk2MTYmTUlEPTUxNzk4JlRFTVBfTUFJTj1TY2llbnRpZmljc19Qb3J0cmFpdC5odG0.html

Abstract

Climate change is predicted to result in rising temperatures which directly influence weed growth. Moreover, alterations in farming practice and variations in the timing of maize sowing affect weeds also indirectly. The main objective of this study was to establish the methodological concept of time-for-climate substitution for use in applied research. For this purpose, a semi-field experiment was conducted with the three important maize weeds *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria viridis*, which were cropped together with maize. In four treatments sowing of weeds was delayed in order to use naturally raising temperatures. This study focusses on late weed growth properties such as tillers, panicles, seeds and biomass as they allow important demographic conclusions for long-term weed population development. Over the season, temperature was continuously monitored with data loggers and growing degree days were calculated in order to relate the late growth properties to the climatic conditions the weeds experienced during early growth in the four treatments. The results from this study suggest that the tested weeds may benefit in two ways: (1) From warmer conditions during seedling emergence and early growth with enhanced vegetative growth and seed set; (2) from more growing degree days available as a result of earlier maize sowing and related extended cropping seasons. We conclude that our methodology is suitable to investigate climate change effects on weeds for applied questions. In order to limit weed growth and weed seed set under future conditions, management measures such as herbicide treatments at later growth stages and earlier harvest of maize should be explored. Furthermore, we suggest that functional relationships between late weed growth properties such as fecundity and different climatic conditions can be used to improve the accuracy of demographic and bioclimatic models.

6 Response of the two rare arable weed species *Lithospermum arvense* and *Scandix pecten-veneris* to climate change conditions

Kristian Peters & Bärbel Gerowitt

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Keywords: climate change; conservation; phenotypic plasticity; rare weed traits; flowering time; biomass; seed production.

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[4] http://link.springer.com/article/10.1007%2Fs11258-014-0358-3

Abstract

Rare weeds are currently under pressure due to intensifying arable management practices, and as a consequence of climate change, these practices will likely become even more intensive, together with a greater uniformity of land use. As a result, ecological stresses will increase for most species of rare weeds, in some cases leading to their further decline or even extinction. Moreover, climate change will alter the suitability of the environment for many plants, since average temperatures are predicted to increase and precipitation extremes to become more common. For most arable weed species it is unclear, whether the anticipated changes in environmental conditions are disadvantageous or beneficial. Little is known about specific biological responses of rare weeds to climate changes, and this study attempts to close some of these knowledge gaps. Here, the rare arable weed *Lithospermum arvense* and the endangered arable species *Scandix pecten-veneris* were investigated with regard to the effects of higher temperature and different crop densities on flowering time, shoot development, plant height, dry mass and seed production. Semi-field experiments were conducted with winter wheat crop for 3 years, involving 48 climate cages, in which every second was a variant of warmer temperature and contrasting crop density. We observed that *S. pecten-veneris* flowered earlier under warmer conditions and had fewer seeds and less biomass in the dense wheat crop compared to control conditions, while *L. arvense* grew taller, it produced fewer seeds in the high density crop. We suggest that such data concerning the biological responses of weeds can improve the precision of bioclimatic distribution models. Finally, we discuss strategies, such as relocation or non-intrusive management practices, for preventing further disappearances of rare arable weeds. Our results should be of considerable interest for the fields of plant ecology, biodiversity research and conservation.

7 Conclusion and outlook

7.1 The cumulated papers in context of this thesis

Within this thesis, four papers are cumulated, starting with a literature review, which is the result of a comprehensive evaluation of research papers. The review covers the topic of shifts and is positioned as an introductory part within this thesis with regard to weeds and climate change in arable ecosystems. The following papers are original research studies covering experiments with weeds at the morphological population scale (see Tab. 3, p. 26). The results of the experiments are of considerable interest for the research fields of weed control, agroecology, plant ecology, biodiversity research and conservation. In the following, the objectives of the four papers are discussed and evaluated.

(1) Review paper „Impact of climate change on weeds in agriculture: a review" (chapter 3, p. 49): In Europe, arable ecosystems and agronomy are under pressure due to the increasing interference of thermophile weeds, late emerging weeds and newly regionally occurring weeds (Schroeder et al., 1993; Weber & Gut, 2005; Gregor, 2006; Otte et al., 2006; Breitsameter et al., 2014). Climate change may further augment this pressure, since it either directly affects the weed species composition, or it indirectly enforces adaptations of management practices to these alterations in climatic conditions (Patterson, 1995; Sala et al., 2000; Olesen & Bindi, 2002; Tubiello et al., 2007).

For sustainable agronomic management strategies, more precise estimations are needed in order to devise an effective weed control and to assure yield (Sala et al., 2000). An understanding of the principal mechanisms underlying these transformations in the arable weed flora is essential to this purpose (Breitsameter et al., 2014). In order to elucidate the processes with regard to the ongoing transformations, the literature review systematically characterises the interrelations between the weeds, the environment and the individual biological responses of weeds with regard to climate change. In contrast to large-scale shifts (Scheffer et al., 2001; Brock et al., 2008; Samhouri et al., 2010), a new concept of small-scale shifts is applied to arable ecosystems. In the literature review, range, trait and niche shifts are connected to climate change and their particular relevance for agriculture and agronomy are highlighted.

So far, with regard to weeds, research has mainly focused on climate-related range shifts. The review ascertains a lack of knowledge concerning trait and niche shifts, which have mainly been described for natural and semi-natural ecosystems. The review reveals that most existing studies recur on meta-analysis of data or on literature data. Original research on shifts is limited for arable weeds. Thus, research approaches are suggested, that are aimed at further improving the estimations of possible future challenges to agriculture and to improve sustainable weed management strategies.

(2) Original research paper: „Important maize weeds profit in growth and reproduction from climate change conditions represented by higher temperatures and reduced humidity” (chapter 4, p. 51): Climate change affects weeds and crops differently. As a result, some weeds may cause higher crop interference in the future (Guillerm et al., 1990; McDonald et al., 2009; Stratonovich et al., 2012). This original research study focuses on the three agronomic important weed species *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria viridis* in maize crop. Currently, these weeds occur numerously in European maize fields and populations are likely to further increase their crop interference (Mehrtens et al., 2005; Otte et al., 2006; Novák et al., 2009; Hyvönen, 2011; Beckie & Tardif, 2012; Oveisi et al., 2013). Despite that there are numerous studies on these weeds, only few studies focused on European populations. Moreover, morphological responses of these weeds are not well understood with regard to alterations in temperatures and precipitation.

This study establishes a new approach of climate chamber experiments. In order to simulate field conditions, large plant tubs were used to grow weeds together with maize crop. In addition to emergence and early growth, generative reproduction and late growth of the plants were studied, which are rarely subject

Fig. 4: Climate chamber experiment with weeds in maize (chapter 4, p. 51). Left: Photo of the climate chamber with simulated current conditions. Right: Photo of the climate chamber with simulated future conditions.

of climate chamber experiments. The experiments were conducted in two climate chambers with climate conditions simulating current climate conditions and predicted future conditions.

To summarize the results, the weed species profited in the order *E. crus-galli*, *S. viridis* and *A. retroflexus* from the climate change conditions. The weeds realized species-specific strategies and responded with different morphological adaptations to the altered conditions. This indicates that there is no universal strategy that is responsible for the arable success of a weed (Jauni & Hyvönen, 2012). Knowledge of the weeds biological responses to the predicted climate conditions helps to predict their future damage potential. The results of this study suggest that a combination of various weed management strategies are needed to ensure control the tested weeds under predicted future conditions.

Fig. 5: Photo of a single treatment the semi-field experiment with weeds in maize in the season 2011 (chapter 5, p. 53).

(3) Original research paper: „Weed growth properties of *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria viridis* as influenced by shifts in the maize cropping season” (chapter 5, p. 53): Climate change leads to alterations in the length of the growing season (Menzel et al., 2003). As a result, maize will be sown earlier under the predicted future conditions (Bloomfield et al., 2006; Walck et al., 2011). Whereas earlier maize sowing results in a prolonged growing season, delayed maize sowing leads to warmer conditions at the time of emergence and during early weed growth. This original research study focuses on these two processes with a semi-field experiment on the three important maize weeds *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria viridis*.

In addition to the varying length of the growing season, the semi-field experiment used naturally rising temperatures in spring to simulate the effect of warmer conditions at the time of seedling emergence and during early growth. Advantage of this methodology is that it allows to study the effects of warmer conditions without manipulating climatic conditions in the field experiment (Dukes, 2007). This is remarkable as other original research studies use different approaches or rely on meta-analyses of secondary sources. The chosen methodology has also limits, such as that the weeds experience different day lengths, which may affect their development. With the chosen approach, the length of the growing season and warmer conditions were studied combined.

The methodology of the semi-field experiment presented in this study provides insight into biological adaptation processes of weeds and functional connections to climate. This study revealed that the tested weeds profit from warmer conditions during seedling emergence with increased vegetative growth and generative reproduction, as well as from longer cropping seasons by adapting their seedling emergence timing parallel to the predicted earlier maize sowing. Furthermore, functional connections such as the fecundity of weeds, as presented in this original research study, can be used to increase the accuracy of bioclimatic models (Holst et al., 2007; Fordham et al., 2012, 2013).

(4) Original research paper: „Response of the two rare arable weed species *Lithospermum arvense* and *Scandix pecten-veneris* to climate change conditions" (chapter 6, p. 55): Climate change exerts direct effects on weeds via changes in temperature and precipitation (Patterson, 1995; Marshall et al., 2003). Due to the lack of original research, for most rare weed species it is unclear, whether the anticipated changes in environmental conditions are beneficial or disadvantageous (Ohlemüller et al., 2006; Lososová et al., 2008; Pompe et al., 2009). As an indirect consequence of climate change, arable management practices are projected to become even more intensive and land use to become more uniform (Baessler & Klotz, 2006; Howden et al., 2007; Neve et al., 2009). Since the survival of most rare weeds currently is threatened due to intensifying management methods, indirect effects of climate change will possibly enlarge the stresses for rare weeds (Olesen & Bindi, 2002; Cimalová & Lososová, 2009). This most likely leads to a further decline of rare arable weeds.

This research study focuses the two rare weeds *Lithospermum arvense* and *Scandix pecten-veneris*. Contrarily to most studies, the whole life-cycle of

Fig. 6: Photo of the experiment with weeds in wheat crop in the season 2012/2013 (chapter 6, p. 55).

the species is focused. Furthermore, a semi-field experimental methodology was established, which has limited technical demands and, thus, can be established under pure field conditions meeting low budget requirements. The semi-field experiments were conducted with winter wheat crop for three years, involving 48 climate cages, of which every second was a variant of warmer temperature and contrasting crop density.

The results of the experiment suggest that the predicted future conditions are disadvantageous for rare weeds most likely due to their limited phenotypic plasticity and properties such as nutrient retention that are obsolete with modern farming (Andreasen et al., 1996; Sutcliffe & Kay, 2000; Baessler & Klotz, 2006; Storkey et al., 2010; Petit et al., 2011). Furthermore, the narrow sociological association of the tested rare weed species suggests that their sociological breadth can be an important precursor for their future status with regard to climate change and future management practices (Silvertown, 2004; Cimalová & Lososová, 2009). This study revealed that for an effective conservation of rare weed species, extensive agriculture must be promoted for communities in which the rare species appear. Strategies such as relocation measures or non-intrusive management practices can additionally prevent further disappearances of rare arable weeds. Results from this study suggest that knowledge of the biological responses of rare weeds are vital for conservation measures to succeed.

The review as first paper cumulated within this thesis covers the population, community and landscape scales of the mechanisms of climate change acting on weeds and the responses of weeds to climate change (Tab. 3, p. 26). The subsequent three papers cover the morphologic population scale with experiments. They focus the whole life-cycle of the weeds, whereas most other studies only focus on emergence and early growth (Storkey, 2005). Nevertheless, early growth parameters are important to assess the competitive ability of weeds in relation to crops. However, as annual weed species invest most of the energy in reproduction in order to germinate from seeds in the following years (Harper, 1961; Grime, 1977), late growth parameters, such as biomass accumulation and seed production, are more elucidative to determine the future development of the weed population than early growth parameters.

Results from the experiments as part of this thesis also allow implications for the other scales. For example, higher seed production and larger growth of a weed suggest a larger niche breadth and, thus, allow implications for the arable weed species composition, as the benefiting species is able to enlarge its status within the community (Chapin et al., 1996, 2000; Booth & Swanton, 2002; Singer et al., 2013). Furthermore, enhanced dispersal capabilities of weeds under climate change conditions suggest, that range expansions performed by the weed species according to climate change will be more distinctive (Lavergne et al., 2010; Matesanz et al., 2010; Richardson et al., 2013). Thus, experiments at the morphologic population scale allow important conclusions and reveal important correlations for the different scales (Tab. 3, p. 26). They are important in order to predict the future role of weeds and to devise sustainable management and conservation strategies.

7.2 Implications and outlook

The evaluation of the experiments at the morphologic population scale as part of this dissertation revealed that data from experiments allow important conclusions for the other scales (section 7.1). In the following, an outlook is presented on how the results from the experiments can be used to increase the accuracy of bioclimatic models at the landscape scale.

Bioclimatic distribution models or habitat suitability models were created to predict the future distribution of plant species with climate change. Fundamental to these models are species' responses to the environment – the so called bioclimatic niche (Elith et al., 2011). Results from the experiments with rare weeds suggest that sometimes there can be a contradiction between the bioclimatic modelling of the species' future distribution and data obtained from experiments (chapter 6, p. 55). Thus, the precision of bioclimatic models has to be improved. To this purpose, spatial modelling can be connected with biological and ecological data. Since, both, conservation measures for rare weeds and weed control for abundant weeds often rely on the accurate prediction resulting from bioclimatic distribution modelling, data on biological and ecological responses of weeds are vital for them to succeed (Morin & Thuiller, 2009; Summers et al., 2012; Kubisch et al., 2013). The three experiments performed as part of this thesis provide a first step toward integration.

Bioclimatic models are used to predict distribution ranges of species under certain climate change scenarios. For reasons of complexity, most bioclimatic models do not incorporate data on biotic interactions, genetic and morphological responses and possible limits of dispersal (Jeschke & Strayer, 2008). As a result, they are more closely aligned with the fundamental niche of the modelled species rather than the realised niche (Monahan, 2009; Austin & Van Niel, 2011). For instance, morphological responses to altered conditions, such as fecundity, can have important effects on the dispersal capabilities of weeds (Nogués-Bravo, 2009; Walther et al., 2009; Bergmann et al., 2010). Moreover, morphological parameters, such as plant height and the number of tillers, have important effects on biotic interactions (the niche breadth) (Lososová et al., 2006; Lososová & Simonová, 2008). These factors are known to greatly influence the distribution range of species (Petit et al., 2011). Fordham et al. (2012) suggest linking a demographic model to biological responses of weeds. Linking morphological responses such as life-history traits with spatial data allows to calculate the population density in relation to altered habitat and climatic parameters (Fordham et al., 2012, 2013). For example, species often occur outside the predicted ranges, which suggest that non-climatic factors are important as well (Jeschke & Strayer, 2008). Furthermore, species with narrow niches in climate space are often modelled more accurately than those with broader niches (Kadmon et al., 2003; Tsoar et al., 2007), which implies that for abundant species the data set has to be functionally filtered (Bürger et al., 2014).

In literature there are already some suggestions on how to extend bioclimatic models with data on species interactions (Araújo & Luoto, 2007; Sutherst et al., 2007) and with dispersal barriers (Midgley et al., 2006). So far, biological parameters were only included in bioclimatic models not related to weeds (Fordham et al., 2012). For weeds, some basic principles have to be considered before including parameters in bioclimatic models. For arable weeds, fecundity and dispersal are key factors regarding the distribution range. Both factors can be modelled as a function to climate and, thus, giving a functional connection. To understand the influence of morphological properties, a simple weed model as proposed by Cousens & Mortimer (1995) can be used to describe this functional connection with regard to fecundity (Fig. 7). Since fecundity is directly correlated to biomass, determining higher biomass under future climate conditions leads to higher fecundity of the species under these conditions (Holst et al., 2007). Following the model of Cousens & Mortimer (1995), the probability of the fecundity (F) will be increased, which will lead to greater dispersal capability of the modelled weed in the following generations (Fig. 7). Species niches and the distribution of the weed will be affected as well (Thuiller et al., 2005).

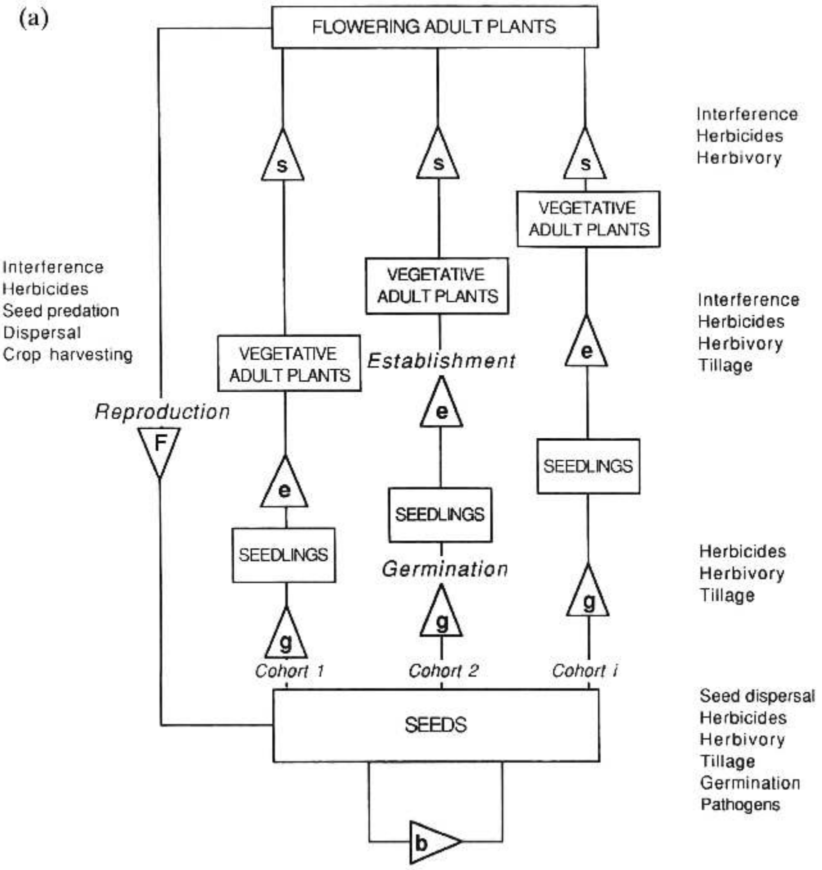

Fig. 7: Flow chart describing a model of the life histories of an annual weed. Cousens & Mortimer (1995), unmodified.

To summarise, altered biological responses of weeds under climate change conditions are functionally connected via simple mathematical or statistical relationships to larger scale processes. These relationships can be included in bioclimatic models (Keith et al., 2008; Anderson et al., 2009; Buckley et al., 2011; Fordham et al., 2013).

Most bioclimatic models determine the distribution of the modelled species with statistical methods (Heikkinen et al., 2006). Several bioclimatic factors are incorporated, such as temperature, precipitation and edaphic factors, which are important for the species under climate change (Heikkinen et al., 2006). In most bioclimatic weed models, statistical regressions of each of the bioclimatic factors with the conditions on-site are performed (Phillips et al., 2006). Each regression gives a functional relationship that can be visualised by a layer (Fig. 8).

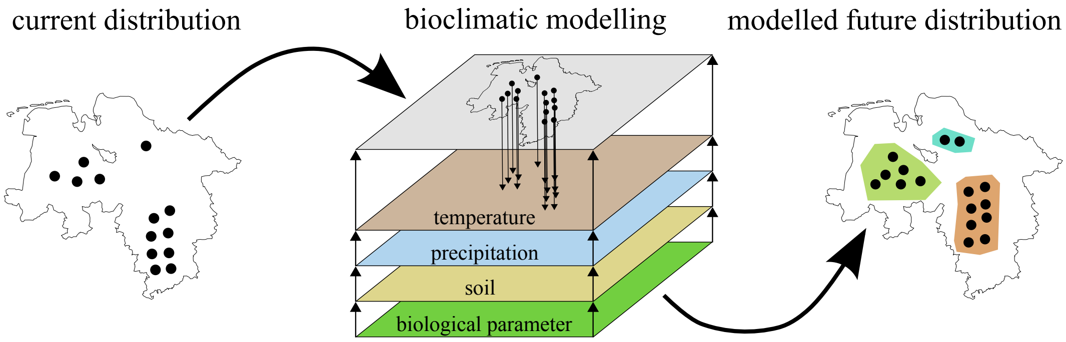

Fig. 8: Functional relationships within a bioclimatic model are arranged as layers. Using the example of Lower Saxony, the current distribution of the weed consists of several occurrences in that area. This occurrence data is used in the bioclimatic model, where temperature, precipitaton, soil and biological parameters define a functional relationship. Adding an additional layer with e.g. biological properties can improve model accuracy.

Including additional biological parameters of weeds basically means to add another layer with a functional relationship (visualised by the green layer in Fig. 8) and to perform regressions with this functional relationship and the conditions on-site. Due to the union of the several layers, occurrence points of the modelled species may be reduced, but accuracy will be improved.

Furthermore, according to Heikkinen et al. (2006), most bioclimatic models are based on climate variables that only describe the current equilibrium distribution of the modelled species. Assuming that an experiment with the species under the predicted climate conditions suggests a different relationship, the equilibrium variables of the model can be adapted according to the outcome of the experiment.

Determining functional connections for weeds in relation to climate seems to play a key role with improving models. The determined functional connections of weed properties in relation to climate as part of this thesis (see chapter 4, p. 51, chapter 5, p. 53 and chapter 6, p. 55) can be used to improve bioclimatic models by means of linking life-history traits, such as fecundity and dispersal, with spatial data (Fordham et al., 2013). For example, through the experimentally determined responses of the weeds, population density can be modelled geographically varying as a function of climate and, thus, identify a species' distribution that is more closely aligned with its realized niche (Fordham et al., 2012).

In order to enable the incorporation of the obtained data into bioclimatic models, future climate-related experiments should be designed to determine correlations between morphological properties or traits of weed species and altered climate conditions. The results of the three original research papers within this cumulative thesis provide a first step towards integration. In this thesis, key factors were determined that allow the modelling of functional connections: fecundity (seed production and biomass at the time of crop harvesting) and vegetative growth (plant height and tillering at the time of early growth). To improve bioclimatic models, more explicit data on biological responses of weeds under distinct climatic conditions are needed.

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8 Summary

Climate change results in alterations in the environment. Changing conditions such as rising temperatures and different precipitation directly affect the biology and ecology of plants. Arable ecosystems are shaped by agriculture and the cultivated crops and associated weeds are a part of them. Here, climate change influences crops and weeds also indirectly by enforcing adaptations of agricultural methods, land use and policy. This cumulative thesis covers the direct and indirect effects of climate change on weeds. In order to face the challenges of future climate change, agriculture is in need of more accurate estimations about potential weed interference to develop effective and sustainable weed control while maintaining crop yield. Whereas conservation needs accurate projections in order to develop strategies to preserve rare species and to prevent their extinction in the long-term. This thesis covers some open questions and knowledge gaps and, furthermore, focuses on the underlying biological and ecological mechanisms of climate induced changes on weeds in arable ecosystems at different scales.

The review paper as first part of this cumulative thesis reveals that the most important outcome of climate change in arable ecosystems are shifts that occur at different scales. Whereas range shifts cover processes at the landscape scale, niche shifts involve ecological processes at the community scale and trait shifts involve biological processes at the population scale. Subsequently, three original research paper, including two semi-field experiments and one climate chamber experiment, reveal that weeds realise species-specific biological strategies in response to altered climate conditions.

The theoretical framework, the findings and data as a result of this thesis provide insights into some underlying biological processes that weeds realise in order to respond to climate change at different scales. Predictions within agriculture and conservation rely on original research data in order to develop sustainable and successful strategies with climate change. These data can be used to increase the accuracy of bioclimatic models further. This thesis also presents proposals to assure harvest and prevent further biodiversity loss in arable ecosystems.

9 Zusammenfassung

Der Klimawandel führt zu Umweltveränderungen wie bspw. steigende Temperaturen und veränderte Niederschläge, die auf direkte Weise die Biologie und Ökologie von Pflanzen beeinflussen. Menschliche Anbaumethoden prägen Agrarökosysteme und angebaute Kulturpflanzen und die assoziierten Beikräuter. Der Klimawandel beeinflusst die Kultur- und Beikrautarten auch indirekt, da Landnutzung, Anbaumethoden und politische Rahmenprogramme dem sich verändernden Klima angepasst werden. Um eine effektive und nachhaltige Beikrautkontrolle bei gleichbleibenden Erträgen sicherzustellen, braucht die Landwirtschaft genauere Prognosen. Dagegen benötigt der Naturschutz Abschätzungen, um nachhaltige Konzepte zu entwickeln, damit das Überleben von gefährdeten Arten auf lange Zeit sichergestellt ist. Diese Dissertation schließt Wissenslücken und behandelt die zugrunde liegenden biologischen und ökologischen Mechanismen des Klimawandels an Beikräutern in Agrarökosystemen auf verschiedenen Skalenebenen.

Als erster kumulierter Teil dieser Dissertation steht ein Review-Artikel, der „Shifts” als die wichtigste Folge des Klimawandels in Agrarökosystemen auf verschiedenen Skalenebenen identifiziert. „Range shifts” wirken auf der Landschaftsebene, „Niche shifts” bewirken ökologische Veränderungen auf Ebene der Pflanzengesellschaft und „Trait shifts” bewirken biologische Veränderungen auf Ebene der Population. Drei Artikel behandeln einen Klimakammer- und zwei Semi-Freiland-Experimente und zeigen, dass Beikrautarten mit spezifischen biologischen Anpassungen auf die veränderten Klimabedingungen reagieren.

Der theoretische Rahmen, die Ergebnisse und die Daten dieser Dissertation geben Einblick in die zugrunde liegenden biologischen Prozesse, die Beikräuter auf verschiedenen Skalenebenen realisieren, um sich dem Klimawandel anzupassen. Landwirtschaft und Naturschutz benötigen diese Daten, um nachhaltige Klimawandel-Strategien zu entwickeln. Diese Dissertation gibt auch Vorschläge, um die zukünftigen Erträge zu sichern und den Artenrückgang zu verhindern. Desweiteren wird diskutiert, wie diese Daten die Genauigkeit von bioklimatischen Modellen verbessern können.

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List of cumulated papers within this thesis

PETERS, K., BREITSAMETER, L. & GEROWITT, B. (2014): Impact of climate change on weeds in agriculture: a review. *Agronomy for Sustainable Development* **34(4)**: 707–721. doi:10.1007/s13593–014–0245–2.

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PETERS, K. & GEROWITT, B. (2015): Weed growth properties of *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria viridis* as influenced by shifts in the maize cropping season. *Journal of Plant Diseases and Protection* **122(1)**: 49–55.

List of abbreviations

A.D.	*Anno Domini* (lat.) – number of years before the estimated birth of Christ
approx.	Approximately
C_3	C_3 carbon fixation pathway in photosynthesis of plants
C_4	C_4 carbon fixation pathway in photosynthesis of plants
CFC	Chlorofluorocarbon
ch.	Chapter
CH_4	Methane
CO_2	Carbon dioxide
e.g.	*Exempli gratia* (lat.) – for example
E.U.	European Union
Fig.	Figure
H_2O	Water
ha	Hectare
lat.	Latin
Mio	Million
N	Nitrogen
N_2O	Nitrous oxide
P	Phosphorus
p.	Page
sp.	Species (singular)
spp.	Several species (plural)
Tab.	Table
UK	United Kingdom

Publication record

Following is a list of publications, which originated within the scope of this thesis.

Articles

Peters, K., Breitsameter, L. & Gerowitt, B. (2014): Impact of climate change on weeds in agriculture: a review. *Agronomy for Sustainable Development* **34(4)**: 707–721. doi:10.1007/s13593–014–0245–2.

Peters, K., Bürger, J. & Gerowitt, B. (2015): Seltene Ackerwildkräuter im Klimawandel – Ergebnisse von Semifeldversuchen und Artverbreitungsmodellierung von *Lithospermum arvense* und *Scandix pecten-veneris*. *Biodiversität und Klima - Vernetzung der Akteure in Deutschland XI. BfN-Skripten* **389**: 50–56. `http://www.bfn.de/fileadmin/BfN/service/Dokumente/skripten/skript389.pdf`.

Peters, K., Edler, B., Steinmann, H.-H. & Gerowitt, B. (2010): Unkräuter unter zukünftigem Klima - Wie beeinflusst der Klimawandel die Unkrautflora? *Julius-Kühn-Archiv* **428**: 331–332.

Peters, K. & Gerowitt, B. (2011a): Auswirkungen des Klimawandels auf die Unkrautarten im Raps. *RAPS* **3/2011**: 8–10.

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Peters, K. & Gerowitt, B. (2012a): Untersuchungen zum Klimawandel mit Unkräutern im Mais - Klimakammerversuche mit *Echinochloa crus-galli*. *Julius-Kühn-Archiv* **438**: 440–441.

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Peters, K. & Gerowitt, B. (2014a): Important maize weeds profit in growth and reproduction from climate change conditions represented by higher temperatures and reduced humidity. *Journal of Applied Botany and Food Quality* **87**: 234–242. doi:10.5073/JABFQ.2014.087.033.

Peters, K. & Gerowitt, B. (2014b): Response of the two rare arable weed species *Lithospermum arvense* and *Scandix pecten-veneris* to climate change conditions. *Plant Ecology* **215(9)**: 1013–1023. doi:10.1007/s11258–014–0358–3.

Peters, K. & Gerowitt, B. (2015): Weed growth properties of *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria viridis* as influenced by shifts in the maize cropping season. *Journal of Plant Diseases and Protection* **122(1)**: 49–55.

Speeches

Peters, K. (2010): Auswirkungen des Klimawandels auf stark gefährdete Segetalarten. *Interdisziplinäres Expertentreffen im Rahmen des Übereinkommens über die biologische Vielfalt.* 16.–20.8.2010, Insel Vilm, Bundesamt für Naturschutz.

Peters, K. (2013): Auswirkungen des Klimawandels auf das Unkrautspektrum. *13. Jahrestagung Syngenta-Services.* 3.12.2013, Potsdam.

Peters, K., Bürger, J. & Gerowitt, B. (2014): Seltene Ackerwildkräuter im Klimawandel – Ergebnisse von Semifeldversuchen und Artverbreitungsmodellierung von *Lithospermum arvense* und *Scandix pecten-veneris. Biodiversität und Klima - Vernetzung der Akteure in Deutschland XI.* 18.-19.8.2014, Insel Vilm, Bundesamt für Naturschutz.

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Posters

Peters, K. & Gerowitt, B. (2011): Zukünftige Problem-Unkräuter im Mais – Klimakammer-Versuche mit ausgewählten Unkrautarten. *KLIFF Statusseminar Pflanzenproduktion.* 10.-11.5.2011, Göttingen.

Peters, K. & Gerowitt, B. (2012): Untersuchungen zum Klimawandel mit Unkräutern im Mais - Klimakammerversuche mit *Echinochloa crus-galli. 58. Deutsche Pflanzenschutztagung.* 10.-14.9.2012, Braunschweig.

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