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Diversity for diversity;

How crop diversity influences weed diversity and trait selection

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'Let the forest come back'
By Donatella Gasparro, 2019

how wonderful the dandelions
taking over the lines of tulips
in your well maintained regularly cut lawn.
how crazy they drive you
the thousands of white warriors
spreading as fast as a puff?
call them invasive, weeds
is there anything more real than this?
why keeping on faking it:
absolutely nothing is under control.

you've tried to fence it, confine it, smooth it to roll
you've tried to sedate it, put it in boxes and square it
simplify it for you to understand, you've tried to organise it, control it, exploit it
thought it could be measured and planned, you pretended for long you could rule it, but no:
nothing out there is under control.

may the burdock grow stronger and taller
may the nettles take over your garden, don't dare pulling out any oak
succession is not an ecological joke

it's what everything wants to do: change, grow wider, fill in every space
overflow and break every vase
escape their own rules when's the case be like the root of the ground elder that's creeping in your vegetable beds: be everywhere – re-sprout from scratch use every cue of a crack

if they put you in a line
start running in circles
throw your seeds in all directions
lignify your skin till the armour of the bark shade this land, protect the young
let the forest come back.

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Abstract

Weeds remain a challenge for organic arable production systems. However, when densities are kept under control, the presence of weed flora can actually provide a range of beneficial functions, both ecologically and agronomically. Additionally, the yield loss potential of the weed community is linked to its species composition. Plant species communities are dynamic, and traits are selected by different filters, of which crop management is one. This sparked the theory that: a greater crop diversity will lead to greater diversity of weed traits, thereby reducing the dominance of single traits and, ultimately, of deleterious weed populations. The application of crop diversity, in the form of intercropping, undersowing, and winter catch crops, could foster this low density but high diversity state. In order to understand this interaction, weed and management data was collected from organic spring cereals fields in 5 different regions in Northern Europe. In addition to the field data, a literature database of problematic weed species was compiled in order to be able to focus on specific weed species or species groups. In several analyses the effect of crop diversity strategies on weed density, diversity, community and traits was studied. First, the crop diversity and site effects, in the form of soil variables, were studied in Germany. Secondly, the regional use of crop diversity, and effects on weeds were studied on organic farms in Denmark, Germany, Finland, Sweden and Latvia. Thirdly, the same dataset was used to test the crop diversity measures for traits selection in the weed community. Results show that direct weed control lowers weed densities, but long term strategies such as winter catch crop use and organic management increase weed diversity, without increasing densities. When looking into trait selection, only a few traits were influenced by crop management and diversity. The traits that were selected for, were not considered problematic. Still, clear and recognizable functional weed groups were observed. The low trait selection is possibly due to the high diversity in well-established organic fields, which increases functional redundancy. These results are promising for both the use of diverse crop management, as well as the implementation of organic management.

Zusammenfassung

Das Vorkommen von Unkräutern ist nach wie vor eine Herausforderung für ökologische Ackerbausysteme. Wenn die Unkrautflora jedoch so bewirtschaftet wird, dass ihr Bestand unter Kontrolle bleibt, kann sie sowohl in ökologischer als auch in agronomischer Hinsicht eine Reihe nützlicher Funktionen erfüllen. Das Schadpotenzial der Unkrautgemeinschaft hängt mit ihrer Artenzusammensetzung zusammen. Unkrautartengemeinschaften sind dynamisch, und ihre spezifischen Eigenschaften werden durch verschiedene Filter, wie das Anbaumanagement, selektiert. Dies führte zu der Theorie, dass sich eine größere Vielfalt im Anbau von Kulturpflanzen auch in einer größeren Vielfalt von Unkrauteigenschaften niederschlägt, so dass sich die Dominanz einzelner Eigenschaften verringert und schädliche Unkrautpopulationen abgeschwächt werden. Mit der Vielfalt im Anbau von Kulturpflanzen wird in dieser Arbeit der Anbau von Hauptkulturpflanzen und Zwischenfrüchte oder Untersaaten beschrieben. Diese vielfältigen Kulturpflanzen können eine Unkrautartengemeinschaft mit geringeren Dichten und einer größeren Diversität erzielen. Um diese Wechselwirkung zu verstehen, wurden Unkraut- und Bewirtschaftungsdaten von ökologisch bewirtschafteten Feldern mit Sommergetreide in 5 verschiedenen Regionen in Nordwesteuropa gesammelt. Neben den Felddaten wurde eine Literaturdatenbank über problematische Unkrautarten mit dem Ziel bestimmte Unkrautarten oder Artengruppen zu selektieren, zusammengestellt. Die Auswirkungen des Anbaus vielfältiger Kulturpflanzen wurde auf die Unkrautdichten, -vielfalt, -gemeinschaft und -eigenschaften untersucht. Zuerst wurden die vielfältigen Kulturen und Standorteffekte, wie Bodeneigenschaften, bezugnehmend auf Deutschland untersucht. Zweitens wurden die Auswirkungen des Anbaus vielfältiger Kulturpflanzen auf Unkräuter in ökologischen Betrieben in Dänemark, Deutschland, Finnland, Schweden und Lettland untersucht. Drittens wurde mit dem gleichen Datensatz der Einfluss der Maßnahmen zur Kulturpflanzenvielfalt auf die Eigenschaften der Unkrautartengemeinschaft getestet. Die Ergebnisse zeigen, dass die direkte Unkrautbekämpfung zu einer Verringerung der Unkrautdichte führt. Langfristige Strategien, wie die Verwendung von Winterdeckfrüchten und die ökologische Bewirtschaftung dagegen erhöhen die Diversität der Unkräuter, ohne dabei die Unkrautdichte zu erhöhen. Bei der Selektion der Eigenschaften wurden nur wenige Merkmale durch die Kulturführung beeinflusst. Es wurden zwar klare und erkennbare funktionelle Gruppen beobachtet, aber keine davon wurde durch die Bewirtschaftung wesentlich beeinflusst, und es wurden auch keine problematischen Merkmale ausgewählt. Dies ist möglicherweise auf die gut etablierten Bio-Felder mit ihrer hohen Diversität und damit einer erhöhten funktionalen Redundanz zurückzuführen. Diese Ergebnisse sind vielversprechend, sowohl für den Einsatz einer vielfältigen Bewirtschaftung als auch für das Verständnis über die Effekte einer ökologischen Bewirtschaftung.

1 General introduction

1.1 Introduction

Weeds have accompanied crops in the field since the dawn of agriculture (Sakamoto, 1982; Vigueira et al., 2013). This flora colonized arable fields from primary succession environments, such as rockslides and river banks, as they are well adapted to the continued soil disturbance. Another group of flora which developed together with the crop, evolved with special adaptations to the environment or even specific crops (Holzner, 1982). The term 'weed' has been defined and re-defined, named and re-named, continuously (Buchholtz, 1967; Holzner, 1982; Sattelmacher, 1987; Zimdahl, 2018). In this thesis, 'weeds', sometimes referred to as 'arable flora', are defined as all species found in the field in addition to the sown crop (Gaba et al., 2016). This choice was made in order to exclude any preconceived judgement on the (dis)service they might provide. This also means any voluntary crops were considered weeds.

"Organic agriculture is a farming system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects." (IFOAM, 2008). Still, it is vital that environmentally friendly approaches such as organic farming also produce reliable yields and stable incomes (Reganold and Wachter, 2016). As organic arable agriculture forgoes the use of chemical herbicides, weed pressure is the largest constraint on crop yield (Alrøe and Halberg, 2008; Penfold et al., 1995; Turner et al., 2007). Of course, organic production systems have control measures available, including direct and cultural control measures, such as harrowing, false seedbeds, tillage, crop genotype choice, cover crops and crop rotations (Bàrberi, 2002). Organic weed control combines direct measures with preventative measures, and has a 'many little hammers' approach, in order to reduce weed resistance and to support weed diversity (Bàrberi, 2002; MacLaren et al., 2020; Mortensen et al., 2012; Storkey and Neve, 2018). This resistance, or adaptation to one type of management, is a term and phenomenon better known in conventional (non-organic) farming, where the over-reliance on herbicides can lead to herbicide resistance in weeds (Jussaume and Ervin, 2016). At the farm system level, however, the 'many little hammers' approach applies to conventional farms too. By combining preventative and cultural weed control with targeted herbicide use, conventional farming systems have the potential to host more diverse weed populations as well (Davis et al., 2012; Ulber et al., 2010).

Regardless of the terminology and farming system, the presence of weeds in a field will impact the environment, by providing both services and disservices. Weeds will compete with the crop for light, nutrients and water, ultimately constraining crop yields. On the positive side, the presence of weeds can support several insect and bird species, and can provide pest control, nutrient cycling, pollination, fix nitrogen, and improve soil structure (Blaix et al., 2018; Gaba et al., 2020; Gerowitt et al., 2017; Marshall et al., 2003). These weed related ecosystem services could consequently provide indirect benefits to the crops, however these effects have not yet been the focus of research. There are also some direct benefits of weeds for the crop, such as stimulating yields by allopathic competition (Søgaard and Doll, 2011) or promoting seed quality (Gibson et al., 2017). However, as MacLaren et al. (2020) hypothesised; these effects might be minor compared to the indirect benefits. There is an increasing interest in species diversity and the community composition of weeds, in relation to crop performance. Adeux (2019) recently found weed diversity and evenness is correlated to decreasing total weed biomass and mitigating crop yield losses. This means that the type of effect on the weed population is not only based on their numbers, but also on the species present and the composition of the community.

Arable farming could therefore benefit from a diverse weed population, as this could lead to improved weed control, increased ecosystem services and crop health. In order to understand the drivers of weed diversity, mechanisms which stimulate individual species, and the functions of individual species, weeds need to be explored with an ecological lens. For example, the community assembly theory can be utilised to better understand the formation and development of weed populations. Any plant community, including arable communities, is dynamic and continuously responds to biotic and abiotic factors (Booth and Swanton, 2002). The species in the community stem from the local species pool; a collection of species present by the existing environment and environmental history (Zobel, 2016). This pool provides the potential species set that is further filtered by the local abiotic conditions and biotic interactions, resulting in the actual community (Belyea and Lancaster, 1999), as illustrated in Figure 1. These filters, also known as constraints or drivers, select species from the pool on the basis of their traits (Navas, 2012). Traits are defined as 'any morphological, physiological or phenological feature measurable at the individual level, from the cell to the whole organism' (Violle et al., 2007). If these traits are considered relevant to the species response to the environment or their effect on the environment, they are commonly referred to as 'functional traits' (Violle et al., 2007). As this thesis focuses on the crop-weed interaction in the context of weed management, the focus will lie on functional traits.

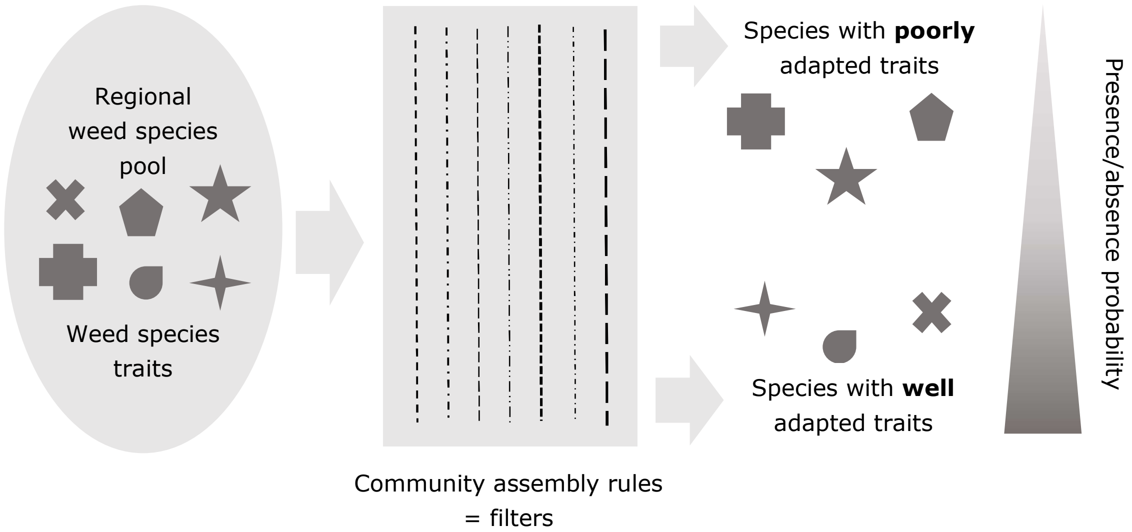

Figure 1. A conceptual model of the trait-based approach to community assembly. The species pool, each with an individual set of traits, is available to occure. To be succesful, the species need to pass through the series of (biotic and abiotic) filters that make certain traits unfavorable. Species and communities that conform to these filters are more likely to occure (after Booth and Swanton (2002) and Weiher and Keddy (1999)).

Agriculture is an environmental driver with management acting as a filter for certain traits (Navas, 2012). The field conditions are the first management factor that impacts weed composition, such as pH, soil texture, and soil drainage (Fried et al., 2008; Hawes et al., 2010). Furthermore, crop management plays a big role as a biotic driver. Present and preceding crop type and tillage all impact weed species traits, and thus shape the community. Firstly, crop type functions as an abiotic filter by dictating the sowing date, the necessary weed control, and fertilisation regime. Secondly, it functions as a biotic filter through the crop-weed interaction, such as light interception (Lososová et al., 2008), which leads to direct competition between crop and weed flora (Jordan, 1993; Zimdahl, 1980). Other elements and management choices of the farming system can also be of importance, for example: crop rotation, tillage depth, and presence of herbivores (Gruber and Claupein, 2009; Olesen et al., 2009; Smith, 2006; Turner et al., 2007). All these elements in the arable system form layers of filters which select for, or against, species on the basis of their traits. The concept of habitat heterogeneity can be applied to understand how management interventions can act as filters on the local weed species pool (Booth and Swanton, 2002). This would practically mean that a greater diversity of crop types, nutrient inputs or cultivation practices will lead to a greater breadth of weed traits, reducing the dominance of single traits (Liebman et al., 2001; MacLaren et al., 2020; Melander et al., 2005; Navas, 2012; Storkey and Neve, 2018). As monotonous uniform management would filter out only a few traits, these traits, and related weed species, get the continuous opportunity to develop into challenges that impact crop production. Thus, a smart layering or alternating of these filters can therefore prevent the build-up or dominance of certain competitive species, such as the alternating of spring or autumn sown crops, open or closed canopies, annual or perennial crops, and a long and varied crop rotation, together with the respective cultivation practices. This approach aims for more balanced weed communities and mitigation of long term weed problems. When continuing this line of thought, crop diversity is another way of layering the effects of crops in space and time. Intercropping, also known as crop mixtures, and undersowing a supportive crop can combine the filtering effects of multiple crops in one field in one season, by competing in multiple niches, leaving fewer or different opportunities for weeds. The addition of cover- or catch crops, adding soil cover when a main crop is absent, can provide crop filters in time, adding nutrient competition and soil disturbances. However, both the theory of diversity for weed diversity (Liebman et al., 2001; MacLaren et al., 2020; Melander et al., 2005; Navas, 2012; Storkey and Neve, 2018) and the effects of crop diversity on weed diversity are hypothesised, but not yet well researched. Although management and environmental factors and their effects on weeds have been studied (Andreasen and Skovgaard, 2009; Fried et al., 2008; Hanzlik and Gerowitt, 2011), it is unclear what effect crop diversity, such as undersowing, intercropping and catch crops have on weed density, diversity, the weed community, and if it selects any weed species traits, especially in organic systems. During the presented chapters in this thesis, this is the question that will be explored.

1.2 Objectives and research questions

The aim of this thesis is to understand the effects of crop diversity on weeds in organically grown spring cereals in Northern Europe. The effects are studied in context of weed management, thus to understand if implemented these measures help mitigate the development of weed problems. The following objective is to understand the effect of crop diversity, in the form of intercropping, undersowing and winter catch crops, on weed density, diversity, the weed community and traits selection.

Research questions:

- Which weed species are considered problematic in spring cereals in Northern Europe?
- What are the weed species found in organically managed spring cereals in Northern Europe?
- How do site and crop management affects weed density, species and diversity in Germany?
- What are crop diversification measures applied internationally?
- What is the effect of crop diversity on weed density, species richness, species diversity and species composition?
- Do region and crop diversification select for weed species traits?

1.3 Chapter outline

In the following chapters of this thesis the above presented research questions have been studied, and the results of the analysis have been the subjects of 5 publications. This section gives an overview of the chapter organisation:

In chapter 2 the project framework and methodology are presented. This chapter further explains and explores the background literature and describes the overall objectives and hypotheses of both the project and the work package which was the basis of this thesis. The objective of this specific research was: to identify practical weed challenges, to investigate the role of crop diversification management for weed management in the field and to cluster weed species into practical groups. Chapter 2 features the design of methodology which will provide the data for this study, the locations of the surveys and the timeframe. The data was collected in 5 different regions in Northern Europe, on organic arable farms over the course of 2 years (2015-2016). In order to avoid the effect on weeds by different crops, one crop type was selected for the study. The crop of choice was spring cereals, as this was a crop type shared in all regions. Field surveys were made by monitoring three subplots of 100 m^2 on each field around the time of flowering. Species were recorded in density classes. In addition, a questionnaire was completed by the farmers on the field management applied on the surveyed fields. The fieldwork was executed by the research partner in each region, and the data was sent in to be analysed. Next to this a literature review was compiled based on existing information about weed occurrence and problems. This information was sourced from literature, grey literature and extension services, by all international partners in their national languages.

In chapter 3 the 'problematic' weed species are identified and explored. The information of the literature review explained in chapter 2 is compiled and organized in order to understand what weeds are deemed problematic in the different regions. To explore how far the expert database reflected the actual situation in the field, these preparatory lists were compared to the actual weed species occurrence found during the field study. The results from this study were used to relate to the species and trait exploration in chapter 6.

In chapter 4 the weed community as affected by crop diversity was studied in the region of northern Germany. The objective was to investigate to what extent environmental factors, crop management factors and crop diversity influenced weed density and diversity. In order to research this objective, weed and management data of spring cereal crops were obtained from organic farms in the region of Mecklenburg-Vorpommern, over the course of two years. The method used was presented in chapter 2, with the addition of soil nutrient data from each field. The impact of the local environment and management factors on the occurring weed communities were studied with multivariate analysis, followed by the separate crop diversity effects in linear mixed models. The results provide an insight in the interactions of site and crop diversity measures on the local weed community.

In chapter 5 the effects of crop diversity on weed density, diversity and the weed community were studied in Denmark, Germany, Finland, Latvia and Sweden. It provides a definition of the crop diversity measures studied and what identifies intercropping, undersowing and winter catch/cover crops. (In this thesis, cover crops were primarily used in the form of winter catch crop, therefore they are referred to as 'winter catch crops' or 'winter cover crops' in the different chapters.) The method used is described in chapter 2. The management data from the questionnaire was analysed for the regional use of crop diversity. Also, this analysis provides an insight in the weed species occurring in organic spring cereal internationally. Mixed models and multivariate analysis were used to answer the analyse the weed and crop diversity data. The results of this study were taken and further explored in chapter 6, as the regions were found to be a strong influence, and crop diversity was found to select for certain weed species.

In chapter 6, the regional and crop management effects were further explored, as they showed to be of influence on the weed community. Thus, they were independently tested to observe whether or not their influence on the community extended into trait selection. The species, management and trait relationships were tested with a fourth-corner analysis, called the RLQ methodology (Dolédec et al., 1996; Dray and Legendre, 2008). As one region (Latvia) displayed regional trait selection, this dataset was removed for the crop management analysis. Then, trait selection by the crop management and crop diversity were analysed in order to understand whether increased crop diversity selects for or against weed traits. This would help to understand the effect of diverse filters for the mitigation of deleterious species or competitive traits. The analysis was then combined with the species list from chapter 3, to explore the overlap between the functional groups.

Chapter 7 discusses the combined findings from the chapters. It deliberates on the combined results, potential patterns, formulates new hypothesis, and, based on these results, gives an outlook for both weed control and weed science.

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2 The impact of crop diversification management on weed communities in summer cereals on organic farms in Northern Europe. An introduction to the study

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2.1 Abstract

This study is a component of the CORE Organic Plus PRODIVA project, a collaboration between international weed research institutions, which aims to improved utilization of crop diversification for weed management in northern European organic arable cropping systems. The overall goal is to maintain a diversified and manageable weed flora that can support beneficial organisms. The objective of this specific research conducted by the Group Crop Health of the University Rostock is: to identify practical weed challenges, to investigate the role of crop diversification management for weed management in the field and to cluster weed species into practical groups. In order to reach this objective a diversity of methods are proposed. Data collection takes place on organic arable farms in five countries (Denmark, Sweden, Finland, Latvia and Germany) over the course of two years (2015-2016). Existing information and literature on weed occurrence and challenges from all regions are compiled into an Ex-ante database and literature review. A two year on farm weed survey is carried out in spring sown cereals and combined with the collection of the field history with a focus on the implementation of crop diversification measures. All data is collected at the University of Rostock for processing and analysing; the survey weed data will be compared with the Ex-ante database and analysed for interactions with the crop diversification measures. Results will both be communicated towards the stakeholders, as well as serve scientific publications.

Keywords: Crop diversity, farmer's participation, field surveys, spring cereals, weed diversity, weed control.

2.2 Introduction

Within organic crop production weeds remain to be the main constrain on crop productivity (Alrøe and Halberg, 2008; Clark et al., 1998; Penfold et al., 1995; Turner et al., 2007). Also in conventional crop production heavy pesticide restrictions and increased public awareness leads to the need to decrease in, and a more efficient use of, herbicides (Melander et al., 2005). This leads to a demand for weed reduction strategies that are both effective and reduce the use and necessity of herbicides in both agricultural systems.

Despite many non-herbicide reduction strategies are available and utilized, a total eradication of the weed flora is not to be expected. This however, leads to highly diverse weed communities within arable fields (Hald, 1999), lacking selection pressure posed by herbicides, increasing the ecosystem services of arable fields (Marshall et al., 2003).

Weed reduction strategies have so far focused on direct mechanical reduction methods like mechanical weeding and thermal treatments. These methods are short term solutions, based on the instant release of weed pressure, and often require a high input of time, fossil energy and can have a negative impact on the soil structure and beneficial organisms (Ascard et al., 2007). This is currently the most wide spread method utilized in organic agriculture.

To support the direct weed intervention there are cultural measures that can be applied. These are preventative techniques adopted into cultivation such as the choice of crop cultivar, adjusted seedbed preparation, the use of mulches and the adjustments in tillage, fertilization and irrigation management (Bàrberi, 2002; Bond and Grundy, 2001; Melander et al., 2005; Mortensen et al., 2000).

Although the combination of mechanical and cultural measures frequently improves weed control on the short term, for a long term continued controlled weed population in organic agriculture the challenge should be put into a wider context and on a higher level. A strong case is made (Bàrberi, 2002) for a transformation in weed management paradigm; the adoption of Cropping System strategies, taking into account the systematic nature of agroecosystems (Ikerd, 1993). These are the long term diversity measures, integrated into the cropping system to create a more balanced and manageable weed community. The maintenance of a higher crop diversity prevents the development of a single weed specie, disrupt weed communities and thus could mitigate severe weed problems on the long run (Blackshaw et al., 2007; Melander et al., 2005). Examples of such crop diversity measures are: a diverse crop sequence, intercropping, cover and catch crops between cash crops and the careful choice and mixture of crop varieties (Bàrberi, 2002; Bond and Grundy, 2001; Melander et al., 2005; Mortensen et al., 2000).

A combination of these measures, direct, cultural and systematic, would create an all-round weed control in agricultural systems with low or no herbicide input. However, many of these crop diversity based techniques are insufficiently studied for their effect on weed communities, especially noxious weed species. Long term crop diversity measures are barely adopted into agricultural practice, partly because of the lack of experience with the application of these strategies and also out of economic restrains (Bond and Grundy, 2001). The lack of adoption is discouraged by the gap that still persist between practical experience and scientific knowledge. For any practical application of these crop diversification strategies, farmers need to be aware of the most severe weed problems. This would require an awareness of the main noxious weed species and how they are effected by cropping system (Gerowitt et al., 2003; Storkey, 2006). On the other side the interaction between research and practice can be more efficient and work with established experiences and methods (Mante and Gerowitt, 2009).

2.3 The PRODIVA Project

Our study is a component of the recently started CORE Organic PRODIVA project, a collaboration between international weed research institutions, which aims to improved utilization of crop diversification for weed management in northern European organic arable cropping systems. The over-all aim is to support organic agriculture with knowledge and tools for the exploitation of crop diversification methods to improve weed management and still maintain a diverse weed flora.

Objectives of the PROVIDA project are: (I) to strengthen the scientific foundation for the employment of crop diversification, (II) to survey the weed situation in practice region-wise and link it to the agronomic measures applied (III) to bridge the information from the surveys with the scientific groundwork (IV) to disseminate important results and recommendation to extension services and growers.

It is hypothesized that crop diversification can improve weed management while ensuring a diverse weed flora by the employment of: (I) pertinent crop sequencing that mitigates noxious weed species (II) improved cover crop establishment with selected competitive cover crop species (III) crop mixtures utilizing the resources better than sole crop species resulting in more weed suppression (IV) variety mixtures exerting a stronger pressure on weed development than the sole varieties.

PRODIVA will identify the potential and strategies for diversifying arable organic crop production systems to improve the management of weeds while maintaining weed diversity and over-all crop productivity. This will be done by capitalizing on terminated and ongoing European research on crop rotation experiments with the inclusion of work packages on crop sequencing / cover crops (Finland, Latvia, Denmark), crop mixtures (Sweden, Poland), and variety mixtures (Denmark, Poland, Latvia). The dynamics of weed, crop and cover crop growth will be determined by recording weed species and densities, and leaf area coverage (LAC) and dry matter accumulation (DMA) over time for each of the three components. This will allow an assessment of their relative proportion changes over time and how that will affect the status of the weed population.

2.4 The work package 'Crop diversification and weed vegetation on farms'

Our objective of this specific research conducted by the Group Crop Health of the University Rostock is: to identify practical weed challenges, to investigate the role of crop diversification management for weed management in the field and to cluster weed species into groups in accordance to their susceptibility for the applied crop diversification techniques.

A literature review is compiled based on existing information about weed occurrences, which includes practical grey sources. This is supported by applied sources from all international partners in their national languages. Based on existing patterns, main weed groups are formed of noxious weeds in major arable crops in organic agriculture in Northern Europe. These findings will be discussed with farmers to align these weed groups with observations in practice. This will be an ex-ante database.

On farm weed surveys are done on 71 farms in five different regions in Northern Europe (Germany, Sweden, Denmark, Finland and Latvia) in two years (2015-2016) using a common methodology. Fields are sampled for weed density and diversity. To minimize the effect of the current crop the surveys focus on spring sown cereals only. Three subplots of 100 m^2 are monitored on each field around the time of flowering, after all weed control measures have been finished, but while both early and late weeds are still identifiable. In these three subplots, species are recovered to density classes. Fieldwork is executed by all respective international partners in their region. Crop diversification data are collected for each field, these include rotation, inclusion of cover crops, crop varieties and crop and or variety mixtures. Data is also collected on weed control measures and local site and soil characteristics. All data is collected at the Crop health group at the University of Rostock where they will be analysed with univariate and multivariate statistics. If existing and accessible, historical, regional or national surveys of relevance will be included in the analyses. Determining factors for weed species compositions and weed densities will be revealed with the help of mixed models and variance partitioning approaches. Revealed factors from the on-farm surveys are compared with the factors investigated in the experiments in the other divisions of the PRODIVA project. The explaining factor for analogies and differences will be identified including weed groups, crop diversification factors and socio-economic dependencies. The latter are identified and discussed at stakeholder meetings.

The perceived outcomes for this study are: scientific contributions on the effect of crop diversification factors on weed communities in organic agriculture. A cross-check of success in weed suppression between scientific knowledge and ongoing experiments and on farm implementation. Points for improved crop diversification strategies are identified and further developed into guidelines for growers and extension services in the participating regions.

2.5 Current progress

The farmers in the German region of Mecklenburg-Vorpommern were approached through adverts in the German magazines for Organic agriculture; Bioland and Biopark. Via this medium we gathered a group of 11 farmers who were interested in participating in the research. During the first year 22 fields were sampled throughout the region (Figure 1), of which 7 were oats, 11 summer barley and 4 summer wheat fields. Only 4 of these fields were a mixed crop, with pea's or clover. Of the international partners partaking in this survey, Denmark surveyed 40 fields in the first year, Sweden and Latvia 20, and Finland 22, making a total of 124 fields surveyed in the first year. The first year's data will be collected and analysed together with the farm management data in the autumn of 2015 for the preliminary results in 2016.

Figure 1 Locations of farms involved in the weed survey in Northern Europe.

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3 Problematic weed species in organic arable agriculture around the Baltic Sea – do fears meet facts?

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3.1 Abstract

Weeds are a perpetual challenge in organic agriculture. The international PRODIVA project studied the effect of crop diversity on the diversity of weed communities, hypothesizing that by increasing the weed diversity, the development of problematic weeds will be mitigated. In order to target the right "problematic" weed species, a preparatory study was conducted to list the most problematic weed species in spring sown cereals in the countries involved in PRODIVA. Therefore, a literature review was conducted in all participating countries, collecting local sources including grey literature, and the opinion of local extension services and other weed experts. From this a list of the most problematic weeds were selected for each country. To explore how far the expert data base reflected the actual situation in the field, these preparatory lists were compared to the actual weed species occurrence found during the field study. Although the expert data often reflected the reality, some species were under- and overestimated, especially non-competitive and monocotyledonous species, respectively. Here adjustment of preconceived notions would be appropriate.

Keywords: problematic weeds, PRODIVA, spring sown cereals, literature review.

3.2 Introduction

Weeds remain the main constraint for organic crop productivity (Alrøe and Halberg, 2008; Clark et al., 1998; Penfold et al., 1995). Non-chemical weed management strategies are available and utilized, which leads to highly diverse weed communities within arable fields (Hald, 1999) and increased ecosystem services of arable fields (Marshall et al., 2003). As the study of Turner et al. (2007) showed, the majority of farmers have a tolerant attitude towards this increased weed presence. What tends to pose a challenge is the build-up of certain weed species populations being highly competitive to the crop, hard to control, build high biomass, cover, or are in other ways decreasing yields. Therefore we consider these specific weeds to be problematic.

The CORE Organic PRODIVA project was a collaboration between international weed research institutions around the Baltic sea, aiming to support organic agriculture with knowledge and tools for the exploitation of crop diversification methods to improve weed management and still maintain a diverse weed flora. Thus, it is hypothesised that a diverse cropping system will lead to diverse weed communities and therefore mitigate the development of problematic weed species, and indeed the first results from the overarching study show an effect of crop diversity on species level (Hofmeijer and Gerowitt, 2018). To increase the understanding of the current knowledge on local problematic weed species persistent in organic production in the Baltic Sea region, an expert database was compiled. Grey literature was excerpted and experts interviewed. However, as Rydberg and Milberg (2000) reported after their field research, sometimes grey literature can be outdated, and fears about the infestation level of certain weeds might prove unfounded, as well as the development of new weeds may remain underestimated. Within PRODIVA field weed data are collected for each country, enabling us to check if the weed species that are mentioned as being problematic are actually prevalent in the fields.

3.3 Material and methods

3.3.1 Expert database

A literature review was conducted in five countries involved in the PRODIVA project, which were Germany, Denmark, Sweden, Finland and Latvia. Sources considered were national scientific literature, specialized literature, grey literature and the knowledge of extension services and specialist in the field. Studied was the state of weed populations and which species were considered ‘problematic’ considering crop-weed competition, weed cover and controllability. This focused on organically grown spring sown cereals. Project partners from the involved countries conducted this search themselves locally, collected information and submitted this to the University Rostock where it was analysed. From this, lists were composed based on the frequency of occurrence of each weed species and how problematic they were considered to be.

3.3.2 Weed survey

The weed survey took place on organic farms in the participating countries. During the two years of this study (2015-2016) 207 spring sown cereal fields were surveyed at the flowering stage of the crop (Stage 61-69 of BBCH scale). Fields were sampled for weed densities and diversity. This was done by estimating the individual density of all weed species found in a subplot of 100 m^2, with a triple replication in each field. These subplots were located randomly in the field, keeping at least 10 meter distance from the field boundary to avoid edge effects. Density estimations were performed species-wise on each field. Here we refer to presence data of the species on all fields per country. Again, data was collected by the partners locally and send to the University of Rostock for analysis. The weed species listed in the expert database were compared to the proportion of fields in which these species were encountered in each studied country.

3.4 Results and discussion

As we can observe in Table 1 there are problematic weed species that are more widely considered challenging, such as *Chenopodium album*, *Polygonum* species, *Centaurea cyanus*, *Elytrigia repens* and *Cirsium arvensis*, and other species that are region specific such as *Anchusa arvensis*, *Thlaspi arvensis* and *Amsinckia micrantha*. This in part can be explained by the subjective and broad notion what defines a problem weed. Here environmental factors such as soil and climate play a role in the development of a local problem, combined with the weed traits that cause a problem, including competitiveness, early emergence, control resistance and sheer numbers produced. Also, in the case of *Amsinckia micrantha* the 'problem' is defined on the basis that this is an invasive plant species, recently discovered in the Danish fields.

From the table three patterns occur. The first being species that cohere well with reality, such as *Chenopodium album*, *Cirsium arvense* and local problems such as *Papaver rhoeas* and *Anchusa arvensis* in Germany, *Erysimum cheiranthoides* in Finland and *Veronica arvensis* in Latvia. Secondly, some species seem to be judged in a different weight, such as *Stellaria media* and *Viola arvensis*, which are common weeds, but, although prevalent, not consistently regarded as problematic. Thirdly are the species that are often presumed problematic in organic cereal production, but were underrepresented in the fields. Notably the monocotyledonous species such as *Apera spica-venti*, *Alopecurus myosuroides*, *Avena fatua* and to a certain extend *Elytrigia repens* are overestimated, the first two are actually connected to winter cereals, so this could be a misjudgement from our field survey which took place in spring cereals. The second two are highly competitive when present, but were not recorded in the field as much as expected.

Weed communities are dynamic and react to many direct and indirect factors. However, the species occurrence holds no information about their health, numbers and development. Regular surveys will support the process of re-adjusting our focus on specific target species as well as our understanding about their control, both locally and internationally. From this comparison we can conclude that although a majority of the expert information is indeed reflected in reality, we can adjust our level of attention to some species, and that the weed community requires continuous observation.

Table 1. Proportion of surveyed fields in which problematic weed species were found for each studied country. Bold are the weed species considered to be problematic in that specific country.

Latin Name	Germany	Denmark	Sweden	Finland	Latvia
Annuals					
Chenopodium album	**0,95**	**0,95**	**0,98**	**1**	**0,65**
Polygonum spp.	**0,95**	**1**	**0,48**	**0,91**	**0,38**
Centaurea cyanus	**0,86**	**0,28**	**0,15**	0,09	**0,53**
Galeopsis spp.	0,12	**0,7**	**0,5**	**0,66**	**0,53**
Stellaria media	**0,83**	**0,95**	0,98	**0,98**	0,8
Galium aparine	**0,19**	0,08	**0,8**	0,95	0,28
Raphanus raphanistrum	**0,43**	0,25	0	0	0,45
Sinapis arvensis	0,07	**0,38**	**0,68**	0	0
Galeopsis tetrahit	0,12	0,38	**0,5**	0,5	0,53
Matricaria inodora	0,71	**0,95**	**0,73**	0,91	0,93
Apera spica-venti	**0,38**	0,1	0	0	**0**
Lamium purpureum	0,38	0,08	0,38	**0,89**	**0,43**
Viola arvensis	0,88	1	0,78	**0,98**	**0,68**
Spergula arvensis	0,1	0,65	**0,43**	**0,68**	0,53
Alopecurus myosuroides	**0,07**	0	0	0	0
Avena fatua	0,02	0,05	0	**0**	0
Papaver rhoeas	**0,76**	0,15	0	0	0
Erysimum cheiranthoides	0	0,1	0,35	**0,98**	0,03
Fumaria officinalis	0,21	0,3	0,85	0,91	**0,38**
Anchusa arvensis	**0,86**	0,73	0	0	0,3
Myosotis arvensis	0,95	0,83	0,50	**0,8**	0,60
Brassica rapa	0,10	**0,25**	0,05	0	0
Thlaspi arvensis	0,64	0,1	**0,5**	0,52	0,50
Veronica arvensis	0,24	0,20	0,18	0,02	**0,83**
Amsinckia micrantha	0	**0,23**	0	0	0
Perennials					
Elytrigia repens	**0,55**	**0,6**	**0,7**	**0,8**	**0,98**
Cirsium arvensis	**0,69**	**0,88**	**0,95**	**0,93**	**0,83**
Equisetum arvense	0,5	**0,15**	**0,53**	**0,36**	**0,88**
Sonchus arvensis	0,21	**0,15**	**0,73**	**0,86**	**0,58**
Rumex spp.	**0,64**	0,38	**0,38**	**0,39**	0,5
Tussilago farfara	0,05	**0,18**	**0,38**	**0,39**	0,10
Ranunculus repens	0	0,5	**0,08**	**0,32**	0,75
Taraxacum officinale	0,14	0,23	**0,68**	**0,64**	0,9
Artemisia vulgaris	0,12	**0,23**	0	0,09	**0,7**

3.5 Acknowledgements

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4 The regional weed vegetation in Organic spring-sown cereals as shaped by local management, crop diversity and site

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4.1 Abstract

Mecklenburg-Vorpommern has one of the highest percentages of organic arable production nationwide. Weeds remain to be the main challenge within this agricultural system. There is also an increase in the national support of agrobiodiversity. Weeds should therefore be continuously kept within manageable limits, while on the other side encourage a specie rich weed flora. Our objective is to investigate to which extent these two aspects can be addressed through the use of diversified crop management. In order to research this objective, weed and management data of spring sown cereal crops were obtained from organic farms in the region over the course of two years (2015-2016). The impact of the local environment and management factors on the occurring weed communities was studied in multivariate analysis approaches, followed by the separate crop diversity effects. We found a fundamental difference between the workings of the short-term management, the long-term crop diversification strategies and the more continuous site variables on the weed vegetation. Weed densities were mostly affected by direct management, while weed diversity and communities were altered through the application of crop diversity variables.

Keywords: Canonical correspondence analysis, weed communities, weed survey.

4.2 Introduction

Within organic crop production weeds remain to be the main constrain on crop productivity (Alrøe and Halberg, 2008; Clark et al., 1998; Penfold et al., 1995; Turner et al., 2007). Despite many non-herbicide reduction strategies available and utilized, a total eradication of the weed flora is not to be expected. Nevertheless, a diverse weed community within arable fields increases the ecosystem services of arable fields (Marshall et al., 2003). The maintenance of a higher crop diversity prevents the development of a single weed species, disrupt weed communities and thus could mitigate severe weed problems on the long run (Blackshaw et al., 2007; Melander et al., 2005). Examples of such crop diversity strategies are: a diverse crop sequence, intercropping, cover and catch crops between cash crops and the careful choice and mixture of crop varieties (Bàrberi, 2002; Bond and Grundy, 2001; Melander et al., 2005; Mortensen et al., 2000). The PRODIVA project (Hofmeijer et al., 2016) aims to study the effects of crop diversification strategies to improve weed management and still maintain a diverse weed flora. This study was conducted within the PRODIVA framework and specifically aimed to research the possible effects of crop diversity strategies on weed communities on farms, thus in practice. We do see that there are many factors of influence on weed communities, such as crop and environment (Andreasen and Skovgaard, 2009; Fried et al., 2008; Hanzlik and Gerowitt, 2011), therefore we aim to investigate a multitude of factors, both in management and site, including crop diversity strategies. This was performed in the German region of Mecklenburg-Vorpommern, with the highest percentage of area under organic production nationwide (BMEL, 2016), which primarily produces organic cereal and beef (LFA, 2017). Like in any other organic arable system, weeds are a perpetual challenge, especially in a region with crop rotations dominated by cereals and grass-clover leys.

Our objectives were to: (I) compile an up-to-date list of weed species in organic farming in Mecklenburg-Vorpommern (II) test influence of site and management factors on: total weed density, species and diversity (III) investigate to which extent density and diversity can be influenced through diversified crop management.

4.3 Materials and methods

A weed survey took place on organic farms in the region of Mecklenburg-Vorpommern in Germany. During the two years of this study (2015-2016) 42 spring sown cereal fields were surveyed at the flowering stage of the crop (Stage 61-69 of BBCH scale), after all weed management measures were finished.

4.3.1 Weed data

Fields were sampled for weed densities and –diversity. This was done by estimating the individual density of all weed species found in a subplot of 100 m^2, with a triple replication in each field. These subplots were located randomly in the field, keeping at least 10 meter distance from the field boundary to avoid edge effects. The density estimation was based on a classification scale, which included 10 density classes, exponentially increasing from 0.2 individuals per m^2 up to over 200 individuals per m^2. Each fields was surveyed once, the following year another spring sown cereal field on the same farm was surveyed. Some individuals could only be identified on genus level and therefore are recorded as such. Latin names are based on the Flora Europaea (EURO+MED, 2006) and in the ordination graphs displayed with EPPO-codes (EPPO, 2017).

4.3.2 Explanatory variables

Farmers were questioned on their overall farm management and the management of the surveyed fields. Information was taken on the current crop, preceding crops for the minimum of 5 years back in the rotation, weed management and yield. Soil type and soil quality ('Ackerzahl') were also inquired and subsequently soil samples were taken from the first 25 cm of the surveyed fields to determine nutrient balances. This was done in the summer of 2016. The soil samples were tested for pH, P2O5, K2O, Mg, S and the CN-ratio. Tillage was not considered, due to similar regimes between farms involved.

The explanatory variables, as shown in Table 1 include: 'Crop Present' which were spring sown cereals including barley, bare or under sown with white clover or peas, oats, bare or under sown with white clover or peas or rye-grass mix, summer rye , triticale and summer wheat. 'Preceding crop' included barley, winter barley, rye, bare or under sown with white clover, spelt, alfalfa, triticale, field beans, cabbage, oats, sunflower, winter wheat, grass glover ley mixtures and maize. 'Other Crops' meaning all other crops then cereals and grass-clover ley. Rotation diversity was based on the presence and mixture of 'Grass clover', 'Cereal' and 'Other crops' for the previous 5 years in the rotation.

4.3.3 Statistical Analysis: R, Linear Models, Multivariate Models

Firstly, we calculated the total weed density, weed species numbers and Shannon indices of all fields. Then we conducted linear models to the data set, to find relationships between each of the explanatory variables and these total weed and diversity data. This was followed by a canonical correspondence analysis (CCA) (ter Braak, 1986) on the whole data set (42 sampled fields, 94 weed species observed, and 25 explanatory variables). Separate CCA's with a single explanatory variable were used to test the Gross Effects of which the significances were tested by permutation test (n=1000). This was followed by the ordination graph from this CCA. For the site conditions a separate dataset was used for the CCA, because from two sites soil nutrient data was missing. Thus, a separate ordination graph expresses these data. All analyses were carried out using the program R 3.4.0 (R Core Team, 2013), making use of the package 'Vegan'.

Table 1. Explanatory variables used in linear models and canonical correspondence analysis.

Variable type	Explanatory variables	Categorious variable - Label	Continuous variable - Unit
Farm	Survey year	2015, 2016	
	Farm type	'Mixed', 'Arable'	
	Organic since	Years under organic management	
Management	Crop present	10 classes	
	Preceding crop	15 classes	
	Seasonal crop sequencing	Dominated by winter or summer crops	
	Yield		tons/ha
	Harrowing	number of	
	Seed density		kg/ha
Crop diversity	Undersown	frequency in 5 years	
	Crop mixtures	frequency in 5 years	
	Catch crop	frequency in 5 years	
	Grass clover	frequency in 5 years	
	Cereals	frequency in 5 years	
	Other crops	frequency in 5 years	
	Rotation diversity	'Low', 'Medium, 'High'	
Site conditions	Soil quality		points
	Sand percentage		%
	Soil pH		
	P2O5		mg/100g dry matter
	K2O		mg/100g dry matter
	Mg		mg/100g dry matter
	N		mg/100g dry matter
	C		mg/100g dry matter
	S		%

4.4 Results

4.4.1 Weed species

A total of 94 weed species were found, of which 62% belonged to the group of annuals, 26% to the perennials. 12 species and/or individuals could only be determined on genus level such as hard to identify species like *Vicia* spp and *Rumex* spp or species that were rare such as *Stachys* spp or *Silene* spp. The majority belonged to the dicotyledons (81%) with the most frequently found species being: *Myosotis arvensis* (98%), *Capsella bursa-pastoris*, *Chenopodium album*, *Fallopia convolvulus* (all 95%), *Vicia* spp (93%) and *Centaurea cyanus* (90%). The most frequently present monocotyledons were: *Elytrigia repens* (58%), *Equisetum arvense* (53%) and *Apera spica-venti* (38%). Of all annual species 40% were known as spring- and 14% whole year germinating species, and 29% autumn germinators.

Table 2. Estimates ± Standard Error of the effects of the explanatory variables on weed density, species numbers, and Shannon Index. Last column shows the CCA gross effects of the variables on the weed composition. Only significant results are shown.

Explanatory variables	Weed densities	Species numbers	Shannon index	CCA effect
Farm				
Survey year		-3,2 ± 1,6˙		
Organic since		0,3 ± 0,2*		0,036**
Management				
Crop present	(B+Cl) 6239±3148˙ (Trit) 3687±1707*	(SR) -13,1 ± 5,3*	(SR) -0,93±0,43*	
Preceding crop	(M) 8295±2995*			
Seasonal crop seq.		(W) 4,2±1,5**		
Harrowing	-1399±649 *		0,22±0,08*	
Crop diversity				
Catch crop			0,18±0,10˙	0,037*
Grass clover				0,026 ˙
Other crops		-2,0±0,9*	-0,13±0,08˙	0,027**
Site conditions				
Soil pH				0,035*
P2O5				
K2O	145±76 ˙		-0,03±0,01**	0,027*
Mg	-299±134*		0,04±0,02*	
S		24,0±14,1 ˙		

P-values associate with linear models outputs. Gross effect was calculated using separate CCAs each with one explanatory variable. P-values associate with permutation tests. ˙P<0.1, *P<0.05, **P<0.01. B+Cl = Barley with clover undersown, Trit. = Summer Triticale, M. = Maize, SR = Summer Rye, W = Winter.

4.4.2 Weed density, species numbers and Shannon index

The influences of the explanatory variables were tested individually on weed densities, species numbers and Shannon index of the surveyed weed flora using Linear Models (Table 2). We found that weed densities were positively influenced by Experience, certain crops like barley, triticale and maize in the previous year, and increased concentrations of potassium. However, repeated mechanical weed management and magnesium concentrations brought densities down.

In species numbers we encountered a time effect. They also increased under organic management, adding a new species every three years. A winter crop dominated rotation increases the species numbers in the field as well as increased sulphur concentrations. Summer rye as the present crop and a higher frequency of other crops in the rotation bring species numbers down.

Like species numbers Shannon indices, were negatively affected by the presence of summer rye and other crops and like weed densities, by potassium and magnesium concentrations. However, Shannon indices were positively affected by repeated harrowing and the presence of catch crops in the rotation which both increased weed diversity.

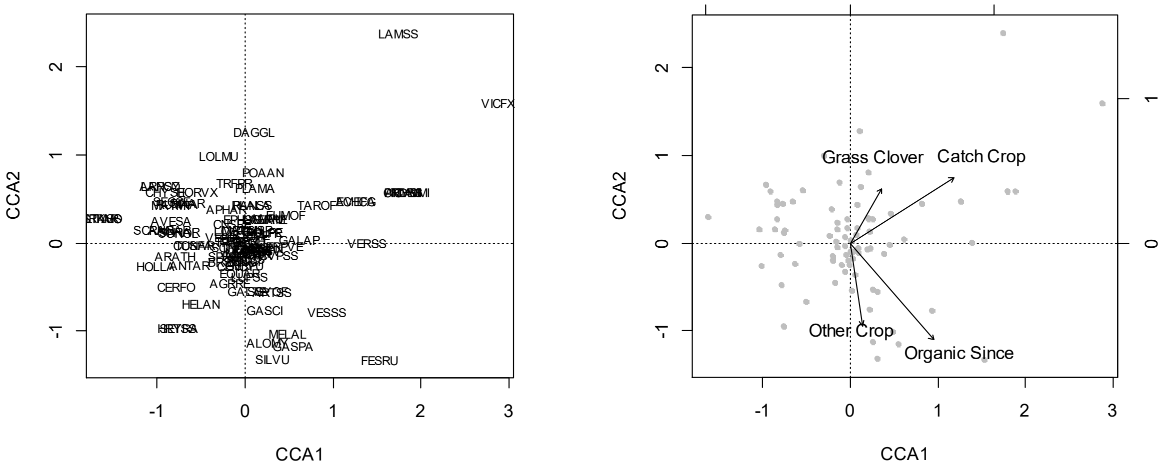

Figure 1 Ordination plots showing the results of the CCA investigation the impact of the crop diversity variables with significant (<0.1) effects on weed communities; "grass clover frequency", "catch crop frequency", "other crop frequency" and "organic since". In the species ordination, names refer to EPPO codes.

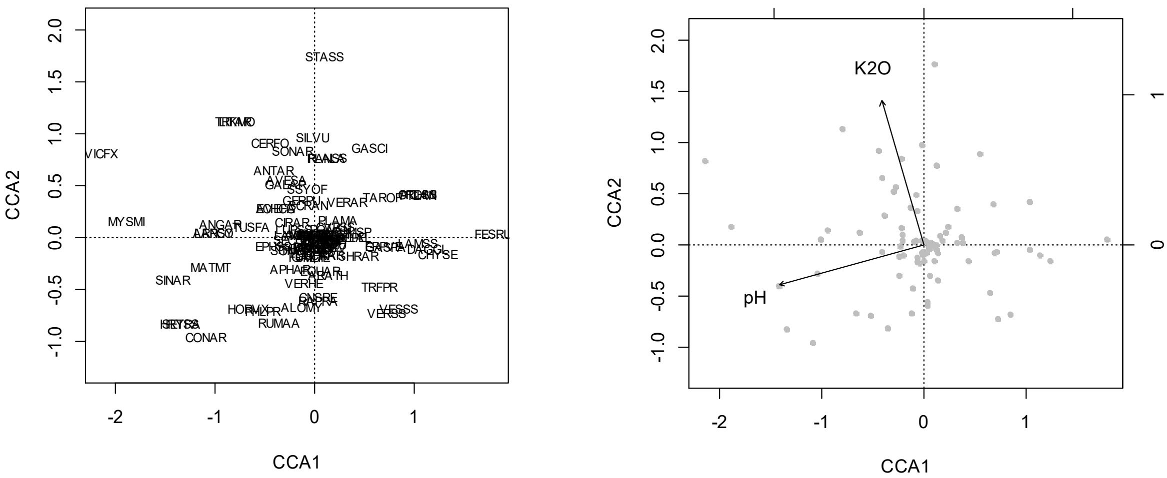

Figure 2 Ordination plots showing the results of the CCA investigation the impact of the Site conditions variables with significant (<0.1) effects on weed communities; soil pH and K2O. In the species ordination, names refer to EPPO codes.

4.4.3 Weed community

The permutation test found an influence of organic since, catch crops, grass clover frequency, other crop frequency, pH, and potassium content (Table 1). The CCA of the farm/management/crop diversity data set resulted in the ordination shown in Figure 1. The axis of 'Grass Clover' indicated the frequency of grass-clover ley used in the rotation which supports monocotyl weed species: *Dactylis glomerata*, *Lolium multiflorum* and *Poa annua* and voluntary red clover *Trifolium pratense*. The second axis of 'Catch Crops' related to the family of *Vicia*, often used in cover crop mixtures. The third axis of 'Organic Since' shows the positive influence on species numbers by the increase of the less common weed species: *Silene latifolia* and other members of the *Silene* family. The forth axis of 'Other Crop' shows a less clear relationship with the weed composition other than the occurrence of voluntary crop species of "other crops" such as *Lupinus spp* and *Helianthus annus* which do not occur in rotations that lack the cultivation of these crops. This is however a broad explanatory variable. Most common weed species clustered mostly in the center, seemingly unaffected by researched variables.

The second ordination (Figure 2) is based on the CCA data set specifically adapted to host the site variables. Here the variables of potassium and pH had a significant effect on the weed composition. The first axis of Potassium appears to relate to species that prefer nutrient rich soils like *Stachys spp*, *Sonchus arvensis* and *Cerastium fontanum*. The second axis of 'pH' associates broadly with species that prefer a light to moderate alkaline soil such as *Sinapis arvensis*, *Matricaria discoidea* and *Setaria spp*.

4.5 Discussion

4.5.1 Weed species

The weed species found in the survey reflect the situation of Mecklenburg-Vorpommern and its agricultural system. The most frequent species were spring- or opportunity based emerging, typical for cereal dominated systems and adapted to the local slightly poorer sandy-loam soils. There was also the occurrence of weeds more often associated with grassland systems, such as *Taraxacum officinale*, *Plantago major* and *Rumex acetosella*, possibly because of the frequent cultivation of grass-clover leys. *Centaurea cyanus* is typically associated with autumn germination and thus autumn sown cereals, it however occurred in high densities in the surveyed spring sown cereals. This species has increased in the last decade in Mecklenburg-Vorpommern and seems to have adopted a more opportunistic lifestyle.

4.5.2 Weed density, species numbers and Shannon index

The most interesting finding on farm level is the increase of species numbers with a longer time under organic management, reaffirming that organic management does over time indeed support species richness (Hald, 1999). Also promising is that the duration of organic management does not increase weed densities. When we look at management effects, a definite effect of crop present was found, both on densities, where some crops are linked with increased densities, and on diversity level. Here we see an effect of summer rye: although densities were not affected, species richness and diversity responded negatively. Rye crops are described to have allelopathy effects on some weed species (Barnes and Putnam, 1986). On the other side: the open nature and late harvest of maize as a pre-crop seems to increase densities the next year. Other authors also record a high impact of crop and pre-crop (Fried et al., 2008; Hanzlik and Gerowitt, 2011). Weeding actually decreases weed densities, but stimulates diversity, an effect also reported by Armengot et al. (2013). The harrowing could weed out early dominant species and stimulate a secondary flush of emergence. Thus, direct management has impact on the densities of weeds in the field, but, a much smaller effect on the weed diversity and non on the weed community as a whole.

In contrast, crop diversity strategies had no effects, positive or negative, on densities, but did on species richness and diversity. Catch crops encouraged diversity, but additional other crops in the rotation decreased it. However, high or low rotation diversity showed no influence. This might be unusual, contradicting research (Ulber et al., 2009), but surveyed rotations also tended to be structurally similar.

Again different were the influences of site variables. The concentrations of the soil nutrients potassium, magnesium and sulphur affected both densities and diversity - reflecting the more complex and intricate effects soil nutrient availability has on densities and specific species (Andreasen and Skovgaard, 2009).

4.5.3 Weed community

If we then look to the CCA's it is promising to find the degree of influence the crop diversity variables have on weed communities. Winter catch crops, grass-clover leys and other crops frequency in the rotation all affected the weed population significantly. This however is in stark contrast to the management variables who, with exception for organic since, do not have any effect on the weed composition. In the soil category the variables affecting are pH and potassium, reflecting the effects from the linear models. However, the more common weed species seemed the least affected by the explanatory variables. Therefore, it is of interest to study these effects on species level in future analysis.

To summarize, most fascinating are the shifted effects from densities that react to direct short-term management and diversity resp. communities that reacts to indirect long-term management. The results are both classical and intriguing and beg for further and deeper research, which will take place within the PRODIVA project.

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5 Crop diversification affects weed communities and densities in organic spring cereal fields in northern Europe

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5.1 Abstract

Within organic crop production, weed interference remains one of the main constraints on productivity, yet diverse weed vegetation supports the ecosystem services of arable fields. The use of crop diversification could alter weed communities and increase diversity, preventing the dominance of single detrimental weed species. This study investigated the type of crop diversification implemented in organic cropping systems in northern Europe and whether this affects the arable weed vegetation. A weed survey was conducted in 207 organic spring-sown cereal fields in five northern European regions (Denmark, Finland, Germany, Latvia and Sweden). Weed density data were combined with management and crop diversification data collected on the farms. The data set was analyzed using linear mixed models and multivariate ordinations. The 197 weed species recorded were representative for the type of organic arable farming conducted in the regions. The management and crop diversification variables studied differed considerably among the regions. Management, such as the type of spring-sown cereal and crop mixture during monitoring, the preceding crop and weed harrowing, primarily influenced weed densities, while weed diversity increased with the duration of organic management and use of winter cover crops. The weed species communities were altered by the crop diversification applied. This study reflects the impact of regionally varied crop diversity and reinforces the importance of regionally adapted crop and weed management.

Keywords: Weed species, crop diversity, cover crops, intercropping, undersowing, weed survey

5.2 Introduction

In organic crop production, weed interference remains one of the main constraints on crop productivity (Alrøe and Halberg, 2008; Penfold et al., 1995; Turner et al., 2007). Weed species richness is usually higher in organic cropping systems and weed communities are more diverse than in conventional farming (Hald, 1999; Hyvönen et al., 2003). The presence of a diverse arable flora increases the ecosystem services of arable fields (Marshall et al., 2003). Despite non-chemical methods being available and utilised, total eradication of the weed flora cannot be expected in either organic or conventional arable systems. Weed management strategies in organic farming particularly focus on physical control methods, such as mechanical and thermal devices. These short-term methods aim to instantly reduce weed pressure on the crop, but they often require a high input of time and fossil energy and can have adverse effects on the soil structure and beneficial organisms (Ascard et al., 2007). Nevertheless, these physical methods are currently the most widespread methods applied in organic agriculture. Cultural measures can also be applied. These are cropping practices, such as the choice of crop cultivar, adjusted seedbed preparation, the use of mulches and modifications in tillage, fertilisation and irrigation management, that can reduce weed emergence and weed competition (Bàrberi, 2002; Bond and Grundy, 2001; Melander et al., 2005; Mortensen et al., 2000). While the combination of direct physical control and cultural measures improves weed control in the short term, there is potential for a long-term build-up of species adapted to organic management and non-chemical weed management. This legacy effect is especially relevant for perennial species that require considerable investment in control measures (Turner et al., 2007). Adopting increased diversity in cropping strategies which is both ecologically based and agronomically sound, is another form of weed control (Gaba et al., 2014). This requires systemic approaches and a shift in the weed management paradigm (Bàrberi, 2002; Ikerd, 1993). These strategies increase the spatial and temporal heterogeneity in a cropping system by adding other environmental filters. Diversification associated with actions like sowing date changes the habitat for weed species in an unpredictable manner (Booth and Swanton, 2002; Gaba et al., 2014). As a result, these actions help farmers to avoid economically injurious dominance of one, or very few, species, and direct the community assembly towards a more balanced weed community of less deleterious weed species (Melander et al., 2005; Storkey and Neve, 2018). More examples of such crop diversification strategies include the undersowing of secondary crops, intercropping and the inclusion of winter cover crops. These crop diversification strategies have been studied for their effects on crop yield (Jensen et al., 2015; Tonitto et al., 2006; Yu et al., 2016) and ecosystem services (Letourneau et al., 2011), but less for their effect on weed community compositions in organic systems. In this study we investigated the type of crop diversification implemented in organic cropping systems in northern Europe, and whether and how these practices affected arable weed vegetation. The specific objectives were: (I) to identify the crop diversification measures practiced in the participating regions of Denmark, Finland, Germany, Latvia and Sweden, and (II) to study the effect of the applied crop diversification on weed vegetation, specifically on total density, species richness, species diversity and weed species composition. These objectives were investigated by conducting a weed survey on 207 fields across different countries with organic spring cereals and linking the records to the cropping measures applied on the fields.

5.3 Materials and methods

5.3.1. Site description and field survey

The weed survey took place on 58 organic farms in the northern European countries of Denmark, Finland, Germany, Latvia and Sweden (Figure 1). Participating farmers/farms were selected from existing networks and local extension services or by voluntarily signing up for the study in response to local advertisements. The survey was conducted in spring-sown cereals during 2015 and 2016. The same farms were visited in both years, but different fields were surveyed each time, as temporal dynamics of the weed community were not the objective of this study. The survey rather followed the crop "spring cereals" within the farm rotation. The actual crop is well-known to have a pronounced influence on the weed vegetation (Hanzlik and Gerowitt, 2016). Therefore, this study on crop diversification focusses one crop type (spring barley, spring wheat, spring rye, oats). In total 207 fields were surveyed at crop anthesis (stage 61–69 of the BBCH-scale) (Meier, 2003), after completion of all physical weed control measures. Weed densities and the number of weed species were assessed for each field. The density of all individual weed species found in a plot of 100 m^2 (2 m * 50 m), with a triple replication in each field, was classified. The plots were randomly placed in the field at least 10 m away from the field boundary to avoid edge effects. Some weed species were impossible to identify at species level at the time of survey and so were only identified and recorded at genus level, such as Vicia sp. In species diversity calculations they are treated as 'species'. A classification scale was applied, which included 10 density classes, exponentially increasing from fewer than 0.2 individuals per m^2 to more than 200 individuals per m^2. For the analyses, the classification scales were adapted into density values using a logarithmic mean. The Latin names are based on the Flora Europaea (EURO+MED, 2006) and in the ordination graphs are displayed with EPPO codes (EPPO, 2017).

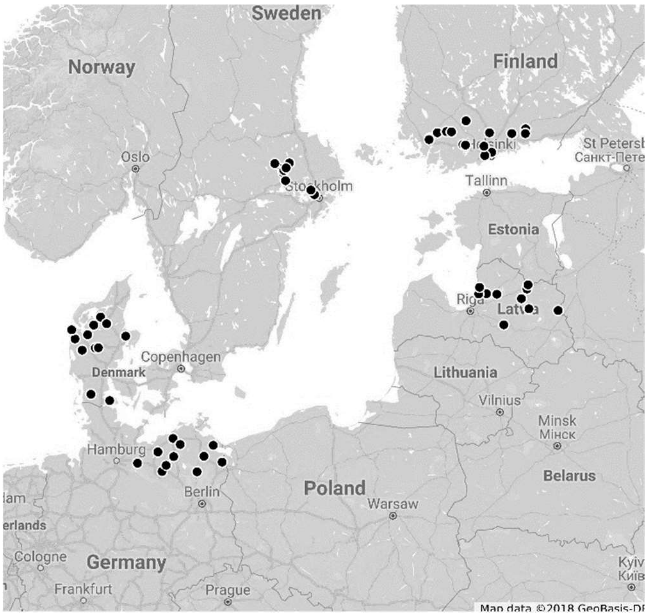

Figure 1 Locations of the organic farms surveyed in Germany, Denmark, Sweden, Finland and Latvia.

5.3.2. Explanatory data

Farmers were visited and completed a questionnaire about their overall farm management and the management of the surveyed fields. The information reflected the current cereal species, the crop sequence for the previous five years, primary tillage, weed management and yield. Site variables such as soil type, temperature and precipitation were also collected. From the farm and field information, 18 explanatory variables were defined based on the research objectives (Table 1). The explanatory variables included 'experience' (the number of years the current farmer had been actively farming), 'years organic' (how long a field had been under organic management), 'crop present' (11 spring cereal categories with different cereal crops of barley (*Hordeum vulgare*), oats (*Avena sativa*), triticale (x *Triticosecale*) and wheat (*Triticum aestivum*) and the presence of a secondary crop), and 'preceding crop' (10 categories in which the majority were cereals and also including the category legumes, which were lupine (*Lupinus sp*.), peas (*Pisum sativum*) or alfalfa (*Medicago sativa*), and other, which included row crops such as potatoes (*Solanum tuberosum*), sunflowers (*Helianthus annuus*) and maize (*Zea mays*), but also buckwheat (*Fagopyrum esculentum*). Seasonal crop sequencing was used to indicate the domination of either winter or summer crops in the rotation. Primary tillage was not considered further as a variable because it appeared that inversion tillage was the common primary tillage practice on all the farms involved in the survey. The variables connected to crop diversity were classified. Crop mixtures were characterised as two main crops, sown and harvested together as cash crops, such as barley and pea mixtures. Undersown crops were characterised as sown into the main crop, but not harvested as a cash crop. Cover crops were characterised as sown when no main crop is present and not harvested as a cash crop. One of the main purposes of a cover crop is to take up nutrients, especially nitrogen, and to prevent nutrient leaching during the winter period (Askegaard et al., 2005). In the five regions studied, cover crops were primarily used as a winter catch crop, therefore they are referred to as winter cover crops. No crop variety mixtures were found in the rotation, although farmers were familiar with this practice. For the explanatory variable, each crop diversity variable was defined by the frequency of use in the last five years of rotation.

Table 1. Explanatory variables used in linear models and canonical correspondence analysis

Variables	Explanatory variables	Unit/label	Variable type
Farm	**Survey year**	2015, 2016	Categorical
	Region	Germany, Sweden, Denmark, Finland, Latvia	
	Experience	year	Continues
	Years organic	year	Continues
Management	**Crop present**	(1) barley (2) barley + clover (3) barley + legume (4) barley + legume + clover (5) oats (6) oats + clover (7) oats + legume (8) oats + legume + clover (9) triticale (10) wheat (11) wheat + clover	Categorical
	Preceding crop	(1) spring cereal (2) spring cereal + clover (3) spring cereal + legume (4) winter cereal (5) winter cereal + clover (6) grass clover (7) rye (8) rye + clover (9) legume (10) other	Categorical
	Seasonal crop sequencing	dominated by winter or summer crops	Categorical
	Yield	t ha^{-1}	Continues
	Weed harrowing	year^{-1}	Integer
	Seed rate	kg ha^{-1}	Continues
	Sand percentage	%	Continues
Crop diversity	**Undersown**	frequency of use in last 5 years	Integer
	Crop mixtures	frequency of use in last 5 years	Integer
	Winter cover crop	frequency of use in last 5 years	Integer
	Grass clover	frequency of use in last 5 years	Integer
	Cereals	frequency of use in last 5 years	Integer
	Other crops	frequency of use in last 5 years	Integer

5.3.3. Statistical analysis

All the analyses were performed in the R environment (R Core Team, 2013) using version 3.4.0 (published April 2017). First, the measured continuous explanatory variables were tested with an ANOVA followed by Tukey tests in order to compare them between regions. The counting (integer) variables that are not normal distributed by definition, were tested with a Kruskal-Wallis test followed by a Pairwise Wilcox test. Second, the mean densities were calculated from the three field repetitions, and then weed species richness and Shannon's diversity index (H) (Shannon and Weaver, 1949) were calculated for all fields using the formula:

$$H = -\sum_{j=1}^{S} p_i \ln p_i$$

p = (n/N)
n = number of individuals of one species
N = total number of individuals
s = the number of species.

The effect of the explanatory variables on weed density, weed species richness and Shannon index was tested using linear mixed models. All the fields were analysed together. Year, region and farm were treated as random factors and farm was also nested in region. The weed densities were log-transformed to obtain homogeneity of variance. The analysis was carried out with the 'lme4' package for R (Bates et al., 2011) for mixed models. Third, a multivariate analysis of the weed species composition was performed to detect the effects of the explanatory variables. The weed species records were used as presence/absence data in the multivariate part, as the large variation in the species density data caused uninterpretable patterns in the multivariate ordinations. A canonical correspondence analysis (CCA) (ter Braak, 1986) was performed on the 94 most common species (frequency of occurrence >3%), using the whole data set: 207 sampled fields and seven explanatory variables (years organic, weed harrowing, undersown, crop mixtures, winter cover crop, grass-clover, cereals, other crops). The investigated regions around the Baltic Sea account for a long environmental gradient. A CCA is more suitable for this long gradient, evident when a redundancy analysis (RDA) with Hellinger-transformed data still resulted in a curved linear gradient in the ordination space (horseshoe effect). Due to the strong regional effect on the site and species distribution, the explanatory variables were recalculated using partial canonical correspondence analysis (pCCA) applying 'region' as a constraint and all remaining variables as co-variables (Hanzlik and Gerowitt, 2011). An ordination graph displays the results and indicates the significant impacts of the variables on the weed community. In order to quantify the effect and significance of each variable, separate canonical correspondence analyses were performed on the data set of the 94 most common weed species to test the gross (eigenvalues) and net effects (proportional eigenvalues) of each single explanatory variable, still applying 'region' as a constraint. Significances were tested by permutation test (n = 1000) as performed by a PERMANOVA implemented in the R function adonis {vegan}. The gross effect was obtained from separate pCCAs, while net effects described the effects of particular variables after partialling out the shared effects (Borcard et al., 1992). Compositional analyses were performed using the 'vegan' package for R (Oksanen et al., 2013).

5.4 Results and discussion

5.4.1. Weed species

In total 197 weed species were recorded and those most frequently recorded are shown in Table 2. The species found are representative of organic arable farming in these northern European regions (Armengot et al., 2012; Glemnitz et al., 2006; Lundkvist et al., 2008; Salonen et al., 2011).

Table 2. The 94 most frequently recorded weed species, their EPPO code and relative frequency based on presence/absence data in 207 fields

Code	Weed species	Relative frequency			
STEME	*Stellaria media* (L.) Cirillo	0.90	MATMT	*Matricaria discoidea* DC.	0.16
VIOAR	*Viola arvensis* Murray	0.86	PLAMA	*Plantago major* L.	0.15
CIRAR	*Cirsium arvense* (L.) Scop.	0.85	SONAS	*Sonchus asper* (L.) Hill	0.15
MATIN	*Tripleurospermum inodorum* (L.) Sch. Bip.	0.84	MENAR	*Mentha arvensis* L.	0.15
CHEAL	*Chenopodium album* L.	0.78	LOTSS	*Lotus* L. sp	0.14
MYOAR	*Myosotis arvensis* (L.) Hill	0.73	PHLPR	*Phleum pratense* L.	0.14
AGRRE	*Elytrigia repens* (L.) Nevski	0.72	STAPA	*Stachys palustris* L.	0.14
POLAV	*Polygonum aviculare subsp. aviculare* L.	0.66	EPHHE	*Euphorbia helioscopia* L.	0.13
POLCO	*Fallopia convolvulus* (L.) Å. Löve	0.65	PTLAN	*Argentina anserina* (L.) Rydb.	0.13
CAPBP	*Capsella bursa-pastoris* (L.) Medik.	0.59	EPHES	*Euphorbia esula* L.	0.12
SPRAR	*Spergula arvensis* L.	0.55	GAEBI	*Galeopsis bifida* Boenn.	0.12
FUMOF	*Fumaria officinalis* L.	0.53	PLAME	*Plantago media* L.	0.12
TAROF	*Taraxacum sect. Taraxacum* F. H. Wigg.	0.51	BARSS	*Barbarea* W. T. Aiton sp	0.12
LAMPU	*Lamium purpureum* L.	0.51	BRSRO	*Brassica rapa subsp. oleifera* (DC.) Metzg.	0.12
EQUAR	*Equisetum arvense* L.	0.48	LOLPE	*Lolium perenne* L.	0.12
LAPCO	*Lapsana communis* L.	0.45	RUMAA	*Rumex acetosella subsp. acetosella* L.	0.12
THLAR	*Thlaspi arvense* L.	0.45	AVESA	*Avena sativa* L.	0.11
SONAR	*Sonchus arvensis* L.	0.40	SONSS	*Sonchus* L. sp	0.11
LYCAR	*Lycopsis arvensis* L.	0.37	CERAR	*Cerastium arvense* L.	0.11
POLPE	*Persicaria maculosa x minor*	0.37	PRASS	*Persicaria* Mill. sp	0.11
GAESS	*Galeopsis* L.	0.35	EPHSS	*Euphorbia* L. sp	0.10
ViCSS	*Vicia* L. sp	0.31	APEVS	*Apera spica-venti* (L.) P. Beauv.	0.10
ERYCH	*Erysimum cheiranthoides* L.	0.30	MATCH	*Matricaria chamomilla* L.	0.10
TRFRE	*Trifolium repens* L.	0.30	LAMSS	*Lamium* L. sp	0.09
CENCY	*Cyanus segetum* Hill	0.29	LTRPR	*Lathyrus pratensis* L.	0.09
VERAR	*Veronica arvensis* L.	0.28	RUMLO	*Rumex longifolius* DC.	0.08
RUMCR	*Rumex crispus* L.	0.27	BRSNN	*Brassica napus* L.	0.08
GALAL	*Galium album* Mill.	0.26	PRUVU	*Prunella vulgaris* L.	0.08
EROCI	*Erodium cicutarium* (L.) L'Hér.	0.26	SECCE	*Secale cereale* L.	0.08
GALSP	*Galium spurium* L.	0.26	SILSS	*Silene* L. sp	0.07
VERPE	*Veronica persica* Poir.	0.26	SONOL	*Sonchus oleraceus* L.	0.07
POLLA	*Persicaria lapathifolia* (L.) Delarbre s. l.	0.25	CHYLE	*Leucanthemum vulgare* (Vaill.) Lam.	0.07
ACHMI	*Achillea millefolium* L.	0.24	RUMCO	*Rumex conglomeratus* Murray	0.07
POAAN	*Ochlopoa annua* (L.) H. Scholz	0.24	FAGES	*Fagopyrum esculentum* Moench	0.06
RANRE	*Ranunculus repens* L.	0.24	RANAC	*Ranunculus acris* L.	0.06
ARTVU	*Artemisia vulgaris* L.	0.22	EPRVE	*Erophila verna* (L.) Chevall.	0.06
TRFSS	*Trifolium* L. sp	0.22	VERHE	*Veronica hederifolia* L.	0.06
CONAR	*Convolvulus arvensis* L.	0.22	VICFX	*Vicia faba* L.	0.06
GERPU	*Geranium pusillum* L.	0.22	APHAR	*Aphanes arvensis L.*	0.05
RAPRA	*Raphanus raphanistrum* L.	0.22	GERSS	*Geranium* L.	0.05
SINAR	*Sinapis arvensis* L.	0.22	VICSA	*Vicia sativa* L.	0.05
TUSFA	*Tussilago farfara* L.	0.22	ANRSY	*Anthriscus sylvestris* (L.) Hoffm.	0.05
GAESP	*Galeopsis speciosa* Mill.	0.21	AMSSS	*Amsinckia* Lehm. sp	0.04
GALAP	*Galium aparine* L.	0.20	ANGAR	*Anagallis arvensis* L.	0.04
PAPRH	*Papaver rhoeas* L.	0.18	BIDTR	*Bidens tripartitus* L.	0.04
CVPCA	*Crepis capillaris* (L.) Wallr.	0.16	BRSRA	*Brassica rapa subsp. campestris* (L.) Clap.	0.04
LAMAM	*Lamium amplexicaule* L.	0.16	GNAUL	*Gnaphalium uliginosum* L.	0.04

5.4.2. Crop diversity applications

The environmental and management variables studied differed greatly between the regions (Table 3). The number of years under organic management was highest for the fields in Germany. On average, the fields in Latvia had been farmed organically for eight years less than in Germany. Soils in the fields in Denmark and northern Germany were sandiest. Average yields in Denmark were twice as high as in Latvia, with the other regions falling in between. Direct weed control through harrowing was applied on fields in most regions almost once on average in the surveyed year. In Finland, only six of the 44 monitored fields had been harrowed. Undersown crops were regularly included in rotations in one of five years in Finland and Latvia, while there were very few cases in northern Germany. Winter cover crops were not cultivated in the most northern regions of Sweden and Finland. In contrast, the inclusion of grass-clover mixtures in the rotations occurred most frequently in Finland, followed by Sweden. Consequently, grain crops dominated the previous rotations in the order Latvia > Germany > Denmark > Sweden > Finland. Crop species mixtures were regularly applied once in five years in Latvia, whereas they played a minor role in all the other regions. The regional use of crop diversification can be described as moderate, with distinct differences between the regions (Table 3). This difference in utilisation between regions can partly be attributed to environmental conditions, such as climate, soil type and erosion risk, which might explain the absence of winter cover crops, particularly in Sweden and Finland due to harsh winters. Moreover, local environmental conditions, culture or local policies (e.g. organic farming subsidy programs) influence farmers' decisions on the implementation of crop diversity in their fields (Dury et al., 2012; Feola et al., 2015; Siebert et al., 2006; Sutherland and Darnhofer, 2012). Hence, 'region' is a factor that usually influences decision-making. In our case 'regions' were sited in different countries, hence national features were likely to influence the implementation of crop diversity. All the countries are EU member states, thus share the Common Agricultural Policy (CAP). The agri-environment scheme as a pillar of the CAP generally supports organic farming. However, economic incentives that vary over time appear to influence how farmers introduce, expand or withdraw different crops from rotations in northern Europe (Peltonen-Sainio et al., 2017). In Denmark, the diversification in cropping systems is mainly motivated by a desire to manage nutrient deficiencies (Jensen et al., 2015). Prevention of nutrient leaching is a principal goal on sandy soils. Furthermore, diversification of the cropping system in organic agriculture is not only implemented for environmental reasons but also to ensure yields. The prevention of nutrient losses and greater access to animal manure might be behind the higher yields in Denmark compared with the other regions. In Finland, legume crops and undersown cover crops are typically included in the crop sequence to increase nitrogen input. Moreover, weed harrowing is less frequent due to the predominance of heavy clay soils in southern Finland and the shortest vegetation period of all regions.

Peltonen-Sainio et al. (2017) report on farmers' desire for more diverse crop rotations based on their adverse experiences with cereal monocultures and soil degradation. Conditions in Sweden are comparable with one exception: undersown crops are used less frequently and their absence directly allows for more harrowing passes. The use of crop diversification in northern Germany can also be characterized as moderate, nevertheless the limited interest in undersown crops here is a major difference from other countries. Due to a much longer growing season and milder winters, autumn-sown crops are used whenever possible, which are less favourable for undersowing. The data indicated another level of crop diversity in organic spring cereal cropping in Latvia. All the management options recorded were used frequently. Crop mixtures were more prominent here than in any other region.

Table 3. Environmental and management variables in the surveyed region

	Denmark	**Finland**	**Germany**	**Latvia**	**Sweden**
Continuous variables	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
Years organic (year)	16.65^{ab} ± 0.9	17.11^{ab} ± 1.24	19.81^{a} ± 1.26	11.70^{c} ± 1.27	16.02^{b} ± 1.26
Yield (t ha^{-1})	4.07^{a} ± 0.14	2.35^{c} ± 0.19	2.86^{b} ± 0.19	1.88^{c} ± 0.19	3.02^{b} ± 0.19
Sand (%)	83.78^{a} ± 2.09	41.88^{c} ± 2.86	77.00^{a} ± 2.91	66.20^{b} ± 2.91	32.41^{d} ± 2.89
Integer variables	Mean/Mode	Mean/Mode	Mean/Mode	Mean/Mode	Mean/Mode
Weed harrowing (times $year^{-1}$)	0.75^{a} / 0	0.23^{b} / 0	0.71^{a} / 0	0.60^{a} / 1	0.88^{a} / 1
Undersown	0.43^{b} / 0	1.05^{a} / 1	0.21^{c} / 0	0.98^{a} / 1	0.56^{b} / 0
Winter cover crop	0.65^{a} / 0	0^{c} / 0	0.41^{b} / 0	0.88^{a} / 1	0.02^{b} / 0
Crop mixtures	0.23^{b} / 0	0.14^{b} / 0	0.22^{b} / 0	0.53^{a} / 1	0.15^{b} / 0
Grass clover	1.10^{ab} / 0	1.34^{a} / 2	1.07^{ab} / 0	0.75^{b} / 0	1.07^{a} / 1
Grain crops	2.90^{bc} / 3	2.50^{c} / 2	3.02^{b} / 3	3.50^{a} / 4	2.70^{bc} / 2
Other crops	0.98^{a} / 1	1.16^{a} / 1	0.64^{b} / 0	0.75^{ab} / 1	1.20^{a} / 0

Mean and standard error of explanatory continues variables per region. Mean and mode for explanatory integer variables. Units are described in Table 1. Variance between regions was tested with ANOVA followed by Tukey tests for continuous variables, and Kruskal-Wallis followed by Pairwise Wilcox tests for integer variables. Letters indicate significant differences between regions ($\alpha < 0.05$) following the results of the Tukey and Wilcox test.

5.4.3. Weed densities, species richness and diversity

5.4.3.1. Weed vegetation variables by region

As with the explanatory variables, the analysed weed data showed differences between regions (Table 4). Weed densities ranged from low numbers of individuals in Denmark to high numbers in Finland and Sweden. The number of weed species identified differed less, with on average 26 species found in each region. Sweden was the only outlier with smaller numbers of recorded species. In the Swedish region, both the high weed densities and low species richness were further reflected in the relatively low Shannon's index. German and Latvian fields had the greatest weed diversity in this study.

5.4.3.2. Weed densities, species richness and diversity affected by environment, management and crop diversity

Interestingly, we found weed densities, species richness, and diversity responded differently to the explanatory variables tested (Table 5). Direct management, such as the cereal crop present, the preceding crop and weed harrowing, mainly influenced weed densities. The cultivation of oats, intercropped with a legume and undersown with a grass-clover mixture, was the only crop present that influenced weed densities. Oats are described as one of the more weed-suppressive cereals (Sarapatka et al., 2009), and the combination with a second crop and an undersowing of clover could have provided the weed suppression observed. This effect was not observed with other cereals, legumes or clover mixtures. The growth of undersown cover crops is often too slow to prevent the flush of early emerging weeds in spring cereals (Salonen and Ketoja, 2020). The preceding crop including rye, even combined with grass clover, caused a spike in weed densities the following year. Rye has been found to be the most weed-suppressive cereal (Lampkin and Padel, 2002), with the capability of suppressing weeds as a standing crop (Akemo et al., 2000; Ateh and Doll, 1996) and as a mulch (Putnam et al., 1983; Schulz et al., 2013). However, in our fields this appeared not to continue into the following year. One explanation for this could be that all the fields were ploughed, hence the surveyed weed offspring of the soil layer largely originated from the crop before winter rye. However, no effect of weed suppression by rye could be confirmed when considering the five previous cropping years. Weed harrowing reduced weed density and species richness (Table 5), hence some weed species were affected more than others by this weed control measure. Armengot et al. (2013) found a similar result in effect strength in a survey of winter cereals on organic farms in Catalonia. Weed densities were reduced by weed harrowing in their study, but this had no influence on species richness. However, weed diversity was not affected by weed harrowing in either the study of Armengot et al. (2013) the present study. Although the literature reports that crop diversity might prove to suppress weeds in rotation (Baumann et al., 2001; Bond and Grundy, 2001; Teasdale, 1996), in the present study weed densities were unaffected by the factor 'crop diversity'. The long-term management did not influence weed densities during the growing season, in contrast to crop choice and weed harrowing. Given that this monitoring covered a large geographical area and very different vegetation periods, similar densities were observed. Other studies that have assessed weeds in the form of biomass or cover confirm the effects of crop diversity (Brandsæter et al., 2012; Breland, 1996; Hartl, 1989; Sjursen et al., 2012). In contrast to density, these variables differentiate for the size of individual plants, but they also change considerably over time (Krähmer et al., 2020). Within cultural control, crop diversity has the important goal of maintain weed diversity, thus a vegetation built by many weed species rather than being dominated by a single or very few species (Storkey and Neve, 2018). The rationale is to prevent high impact species to develop populations, which causes severe economically relevant yield damage. If made up by different species, including low growing dicotyledons, the same weed density will cause less yield loss than made up by few tall and strong growing ones. Long-term strategic management decisions, such as crop diversity measures and the length of organic farming, influenced weed diversity more than weed densities. The use of winter cover crops was found to increase weed diversity (Table 5). This crop diversity measure increased the number of field operations during the year, such as seedbed preparation in autumn and termination of the cover crop. This is likely to increase the weed species spectrum occurring during the growing season, adding species from the local pool of the seed bank. Which species emerge from this pool depends on the time of soil disturbance in the year. This is spring for spring cereals, and autumn for winter cover crops. Hence, the percentage of species emerging from the total spectrum of a site increased. If these species are allowed to reproduce, they can also increase their propagule pressure. In regions where winter cover crops can be grown, these may not only be an important source for maintaining nitrogen in the root zone, but may also improve weed species diversity. The benefit of organic farming on biodiversity, when compared to conventional, has been shown for various organisms, including species diversity of arable flora (Bengtsson et al., 2005; Fuller et al., 2005; Hole et al., 2005; Mäder et al., 2002). These comparisons are done with different fields. Our data hints at a field-specific effects resulting from the length of organic management: weed species richness and weed diversity increased over time, with one extra species appearing in the weed community every five years of organic management (Table 5). Furthermore, increased time under organic management did not increase weed densities. These two results suggest that increases in weed species richness do not necessarily portend an increase in weed densities.

Table 4. Weed variables in the surveyed region

	Denmark	**Finland**	**Germany**	**Latvia**	**Sweden**
Weed variables	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
Weed density[1] (Individuals m^{-2})	27.85^{d} ± 10.69	96.19^{ab} ± 14.78	71.45^{b} ± 14.94	44.54^{c} ± 15.12	166.80^{a} ± 15.03
Species richness (no.)	26.83^{a} ± 0.82	26.21^{a} ± 1.15	25.93^{a} ± 1.16	27.03^{a} ± 1.18	20.39^{b} ± 1.17
Weed diversity (Shannon's index)	1.98^{ab} ± 0.07	1.75^{bc} ± 0.10	2.11^{a} ± 0.10	2.14^{a} ± 0.10	1.62^{c} ± 0.10

Mean and standard error of weed variables per region. Variance between regions was tested with ANOVA followed by Tukey test. [1]Weed density values were log transformed for the analysis; re-transformed estimates and standard error values are displayed in this table. Letters indicate significant differences between regions (α < 0.05) for both statistic tests.

Table 5. Results from linear mixed models for management, crop diversity and environmental variables, and their effects on total weed density, species richness and weed diversity

	Weed densities[1] (individuals m^{-2})	Species richness (no.)	Weed diversity (Shannon's index)
Explanatory variables	Estimate±SE	Estimate±SE	Estimate±SE
Farm			
Survey year	Random	Random	Random
Region (farm)	Random	Random	Random
Experience	ns	ns	ns
Years organic	ns	0.22 ± 0.064**	0.024 ± 0.005***
Management			
Crop present	Oat/L/GC -53.12 ± 48.64 ·	ns	ns
Preceding crop	Legume 2.90 ± 15.26 · Other 22.17 ± 18.22 · Rye 27.48 ± 16.83 ** Rye/GC 44.55 ± 6.72 **	ns	ns
Seasonal crop sequencing	ns	ns	ns
Yield	ns	ns	ns
Weed harrowing	-11.88 ± 6.72 *	-1.18 ± 0.51*	ns
Seed density	ns	ns	ns
Growing days	ns	ns	ns
Crop diversity			
Undersown	ns	ns	ns
Crop mixtures	ns	ns	ns
Winter cover crop	ns	2.24 ± 0.65***	0.17 ± 0.054**
Grass clover	ns	ns	ns
Cereals	ns	ns	ns
Other crops	ns	ns	ns

p<0.1 ·, p<0.05 *, p<0.01**, p<0.001***. ns: not significant. Region and year are random factors, farm is nested in region.
[1]P values for weed densities were calculated using log-transformed values, untransformed weed density estimates and standard error values are displayed in this table. L = legume crop, GC = grass-clover.

5.4.4. Effects of crop diversity and management variables on the weed community

While all tested explanatory variables statistically influenced the weed community for the most common species (Table 6), the magnitudes of the effects were small. Hence, even though the weed species community showed a weak reaction to the explanatory variables tested in the multivariate analysis, they still loaded on the tested variables. The crop present and the preceding crop had the greatest net effect on weed species composition. For one of the regions (Denmark), Andreasen and Skovgaard (2009) found an even stronger influence of these variables on weed communities. The pCCA ordination with "region" as a constraint positions the most common species, such as *Stellaria media*, *Viola arvensis*, *Cirsium arvense*, *Tripleurospermum inodorum* and *Chenopodium album*, in the more neutral central position (Figure 2, species in the center not all shown for readability). The species further from the centre, hence more loaded on specific conditions, included many grassland species.

On fields under arable use for at least the five years recorded, with most of them probably under arable use for much longer, grassland species occurred strikingly frequently. While grassland species are adapted to management consisting of repeated above ground defoliation, arable species are adapted to stand inversion soil tillage. As grassland is often less uniformly used compared to arable land, the observed specialization to local abiotic conditions is broader. If organic farming allows grassland species to migrate into arable fields, these species still react more specific to local conditions.

Table 6. Gross and net effects of explanatory variables on weed species composition

	Total weed species (197)			**Most common (94)**		
Explanatory variables	Gross effect	Net effect		Gross effect	Net effect	
Farm						
Experience	0.033	0.005	*	0.009	0.003	
Years organic	0.039	0.006	***	0.071	0.025	***
Management						
Crop present	0.844	0.130	***	0.267	0.093	***
Preceding crop	1.070	0.170	***	0.400	0.139	***
Weed harrowing	0.041	0.006	***	0.019	0.006	***
Seasonal crop	0.032	0.005	**	0.012	0.004	**
Sequencing						
Crop diversity						
Undersown	0.031	0.005	***	0.012	0.004	***
Crop mixtures	0.027	0.004	***	0.013	0.004	***
Winter cover crop	0.052	0.008	***	0.024	0.008	***
Grass clover	0.038	0.006	*	0.014	0.005	*
Cereals	0.037	0.006	***	0.011	0.004	***
Other crops	0.027	0.004	*	0.011	0.004	*

Ordination (pCCA) eigenvalues (gross effect) and proportional eigenvalues (net effect) from the total (197) and the most common (94) weed species recorded. 'Region' was used as a constraint. p<0.05 *, p<0.01**, p<0.001***.

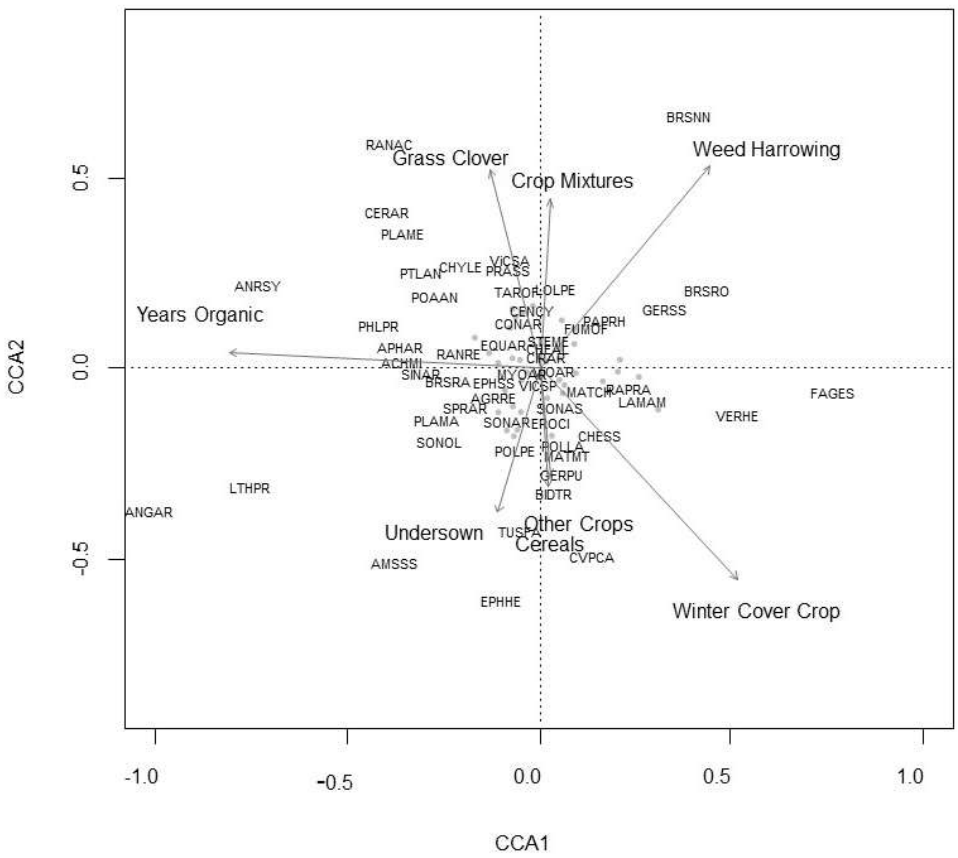

Figure 2 Ordination plot (pCCA) showing the impact of management and crop diversity on the weed species composition of the 94 most common species recorded. Some of the species in the central positions are shown only by points to increase readability. Eight explanatory variables with a significant effect on the species composition are shown. pCCA is calculated with 'region' as a constraint.

The pCCA ordination plot identified the major effects of explanatory variables on the weed community. The less common, but still frequent weed species responded more strongly to these variables. The species *Sinapis arvensis*, *Ranunculus repens*, *Aphanes arvenis* and *Phleum pratense* positioned themselves along the axes of length of organic management (years organic), hence the longer the field is under organic management, the more these species occur. Winter annuals such as *Veronica hederifolia* and *Lamium amplexicaule* were positioned in the other direction and thus loaded more on less time under organic management. The weed community monitored in spring cereals reveals few arable perennial weeds species loaded on the years organic. This does not mean that these species are not present, but rather they agglomerate in the centre, hence are common under all monitored situations. Organic farming frequently suffers from perennial arable weeds (Melander et al., 2016; Rasmussen et al., 2014). *Sinapis arvensis* is a species with large seedlings known to be difficult to control mechanically in the long term (Melander et al., 2018). Weed harrowing selects for species with large seedlings because the plants survive, re-root, and produce seeds. In organic farming more seedlings will induce more harrowing the following year and so on. Consequently, with time of organic cropping, S. arvensis occurred more often. Therefore, in the ordination *Sinapis arvensis* loaded positively on 'years organic' more than on 'weed harrowing'. In contrast, *Brassica napus*, which as a volunteer crop does not build up a long-living, dormant seedbank, loaded on weed harrowing. Hence, the species either occurred after frequent harrowing or was even induced by it. The factor 'winter cover crop' was pronounced and identified grassland species such as *Potentilla ansernia*, *Plantago media*, *Cerastium arvense*, *Poa annua* and *Leucanthemum vulgare* that loaded positively on the reduction of winter cover cropping. *Chenopodium* species (CHESS), and to a lesser extent other annuals, increasingly occurred along with the frequency of these cover crops. Hence, the pCCA revealed that perennials and annuals responded diametrically opposite to winter cover cropping. We suggest that winter cover crops may reduce perennial species directly through competitive exclusion and indirectly through the increased disturbance by cover crop husbandry (Blackshaw et al., 2007; Hǻkansson, 2003). The use of grass-clover leys is oriented opposite to winter cover crops in the vector space of weed communities, indicating a reverse effect. However, arable annuals and grassland perennials loaded less dissimilarly to grass-clover cropping than to winter cover cropping. Cropping grass-clover leys resulted in the increase of legume species such as *Vicia* and perennial grassland species such as *Taraxacum officinale* and *Lolium perenne*. Crop mixtures and undersown crops revealed a less pronounced influence on weed community structure than either grass-clover or winter cover crops, as evidenced by their vector length and the lack of species positioned around these factors.

5.5 Conclusions

This study has provided an overview of as well as insights into the use and effects of crop diversity. Although the regions shared many species common in organic agriculture, the weed vegetation in detail was regionally different. The weed species communities were altered by the use of crop diversification. This reflects the impact of a regionally varied use of crop diversity and emphasises the relevance of regionally adapted and mutually adjusted crop and weed management. It was particularly striking to find effects of crop diversity and management variables despite this regional diversity in the data. Worth noting was the different reaction of weeds to direct management and long-term management. While weed densities were influenced by weed harrowing and crop choice, weed diversity was increased by the length of organic management and use of winter cover crops. The effect strength of the explanatory variables in the weed community reflected the interactions in total weed densities and weed diversity, where years organic, weed harrowing and winter cover crops also displayed the strongest effects. Clearly, any pan-regional recommendation on crop diversity as weed management must encompass a screening for regional applicability. The result will inevitably shape the arable weed vegetation. Beside this advocacy for regional adaptations, we recommend to compile the arable system in a way that any disturbance by management is realized with an intermittent periodicity. This should allow different species to establish every now and then, but prevent patterns re-enforcing selected ones over time. In case of too many weeds, direct physical control can reduce densities. However, the manner in which the individual species in the community interacted with the explanatory variables suggests that crop diversification might have more complex effects at individual species level, which have to be investigated further.

5.6 Acknowledgements

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6 Weed species trait selection as shaped by region and crop diversity in organically managed spring cereals.

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6.1 Abstract

Weeds remain a challenge in organic arable farming, as well as supply ecosystem services. The aim is to control weed densities while hosting a diverse and manageable weed community, preventing domination of few deleterious species. Therefore, we want to understand how specific species are stimulated, and which traits are selected for. This study focuses on crop diversity hypothesizing that (1) regions and (2) crop diversity function as filters for specific weed species traits. We conducted a weed monitoring in spring cereals over 2 years on organic farms in five northern European regions. Management and weed trait variables collected for the occurring species allowed an RLQ fourth-corner analysis. The weed communities were regionally specific, but trait selection was not observed, except in Latvia. Hence, the regional species pool provided different species with similar traits. Crop diversity within the management of spring cereals, such as undersowing and cereal frequency in the rotation, affected weed traits. The number of years under organic production selected no traits, although species numbers are known to increase. Hence, general weed species diversity increased, irrespective of traits. We conclude that organic management may support the agility within the weed community against selection of species and act as a buffer rather than as filter.

Keywords: undersowing, winter catch crops, crop mixtures, arable flora, community assembly, Baltic area, northern Europe

6.2 Introduction

During the last few decades, the floral diversity in arable fields has declined severely, driven among others by the use of fertilizers and herbicides (Fried et al., 2009; Storkey et al., 2012). The presence of weeds provides, however, a plethora of beneficial ecosystem services in arable fields (Marshall et al., 2003). Therefore, a more sustainable weed management is an important step toward ecological intensification (Petit et al., 2015). On the other hand, weed pressure still remains the main production-limiting factor in agricultural systems, especially in those systems forgoing the use of herbicides (Alrøe and Halberg, 2008; Penfold et al., 1995; Turner et al., 2007). Thus, the aim is to continue controlling weeds and, within the remaining weed community, host weakly competitive and manageable species in the absence of herbicides. There have been arguments made for balanced weed communities, in order to mitigate weed problems (Melander et al., 2005; Storkey and Neve, 2018). Furthermore, there are signs indicating that weed diversity and evenness are capable of decreasing total weed biomass, as well as mitigating crop yield losses (Adeux et al., 2019).

High weed functional diversity, with more evenly distributed weed functional space, might lower competition pressure (Macarthur and Levins, 1967; Navas, 2012). In order to form agronomically innocuous, diverse, and controllable weed communities, we need to understand how these communities are composed, how specific species are stimulated, and which traits are selected for. In the last few decades, the theory of community assembly has been successfully applied to describe the formation and development of weed populations (Booth and Swanton, 2002; Gaba et al., 2014; Navas, 2012; Storkey et al., 2010). Trait-based research is argued to be the next step forward in understanding weed diversity and competitiveness (Storkey and Neve, 2018), as well as in exploring how environment and management can be modified to select for certain preferred traits in the community. Specific weed species can be promoted or discouraged through the selection in specific traits by repetitive and strong filters (Booth and Swanton, 2002). These filters include the timing of management, especially the timing of soil disturbance, such as tillage or harrowing, and the crop choice along with sowing time (Booth and Swanton, 2002; Gaba et al., 2014; Gunton et al., 2011; Smith, 2006). Crop diversity, temporal and spatial, such as the use of catch crops, intercropping, undersowing, and a diverse crop rotation, could all form another layer of filters, via additional competition for light, soil disturbance, and niche differentiation (Hofmeijer et al., 2021; Navas, 2012). However, how specific traits are affected by crop diversity factors is still unclear.

From the research done so far, there appears to be a hierarchy of filters and disturbances from both environment (local conditions) and management (crop abiotic factors) (Gaba et al., 2014; Navas, 2012). As Navas (2012) proposed, the local soil conditions and climate determine the local species pool available, as well as shape crop management. This larger influence of environmental factors on the weed community has been well studied (Andreasen and Skovgaard, 2009; Fried et al., 2019, 2008; Hanzlik and Gerowitt, 2011; Salonen, 1993). Management factors, such as herbicide use, in addition to crop sowing date and tillage, are considered strong filters for the composition of weed communities, but strengths of the filters vary (Armengot et al., 2016; Fried et al., 2012; Gunton et al., 2011; Navas, 2012; Smith, 2006). The crop present is often a much stronger filter than other elements in the rotation (Fried et al., 2008; Meiss et al., 2010; Navas, 2012; Smith, 2006). The present crop creates a specific ecological condition (Hallgren et al., 1999) and is associated with its crop specific management practices (Andersson and Milberg, 1998). Rotational elements, such as the effect of previous crop types, use of grass-clover ley, undersowing, intercropping, cover cropping, and general crop diversity seem inundated as a filter, taking place in the community already shaped by the stronger primary filters.

Our research focused on the weed community in organic spring cereals in northern European regions and, thus, farming systems without herbicides, in one crop type, with similar tillage regimes. We studied the possible selection of traits in the community by the filters of regional environment and crop rotational elements, with a specific interest in crop management and crop diversity. The weed traits of interest were related to growth (life form, growth form, Grime's life strategy), life cycle (duration of flowering, germination), and physiology (specific leaf area, plant height, seed weight, affinity to soil nutrient conditions). Firstly, as the data were collected in five different regions (Denmark, Finland, Germany, Latvia, and Sweden), there was large variation in environmental conditions, climate, and geography. Previous studies have indicated effects of environmental factors on weed communities (Fried et al., 2019, 2008; Pinke et al., 2010), but it remains unclear if the regions and their specific management were selecting for specific traits. Secondly, we were interested in the effect of crop diversity on weed diversity. In a previous study on the data, we observed selection for specific weed species across regions (Hofmeijer et al., 2021). Thus, we expect trait selection to cause these reaction patterns. This led to the first hypothesis that regions, with their specific environment, are a strong filter for traits in the weed community. By collecting the data in one crop type, we bypassed the known strong filtering factor of different crops present, allowing for better insight into more subtle and historical cropping filters. Thus, within the chosen study crop spring cereals, we secondly hypothesize that crop diversity and crop management select for weeds with certain traits.

6.3 Materials and methods

6.3.1. Vegetation data

A weed survey was conducted on 58 organic farms in the northern European countries of Denmark, Finland, Germany, Latvia, and Sweden (Figure A1, Appendix A) (Hofmeijer et al., 2021). The survey was conducted in spring cereals during 2015 and 2016. In total, 207 fields were monitored at the crop flowering stage (stages 61–69 of the BBCH scale) (Meier, 2003), after all physical weed control measures were completed. During the survey, weed densities and the number of weed species were documented for each field. Within these arable fields, three plots of 100 m^2 were surveyed for the density of all individual weed species. To estimate the densities, a classification scale was used, which included 10 density classes, exponentially increasing from fewer than 0.2 individuals per m^2 to more than 200 individuals per m^2. To avoid edge effects, the plots were randomly located in the field, at least 10 m away from the nearest boundary. Several weed species were impossible to identify at time of the survey and, thus, only classified and recorded at the genus level, such as *Vicia spp*. To allow for analysis, the classification scale was converted into density values using a logarithmic mean. The Latin names were sourced from the Flora Europaea (EURO+MED, 2006), and species are displayed in the ordination graph with EPPO codes (EPPO, 2021).

6.3.2. Crop management and environmental data

The farmers whose fields were surveyed completed a questionnaire about their farm and field management. From this, information was documented about the site, the current cereal species, the crop sequence for the previous 5 years, primary tillage, weed management, and yield. From the farm and field information, five classes of environmental or management data were selected for the research objective: (1) 'crop' (if the cereal crop present is sown on its own, intercropped, or undersown), (2) 'pre-crop' (if the preceding crop in rotation was a spring cereal, winter cereal, grass-clover ley, row crop, or other spring sown crop), (3) 'crop diversity frequency' (the number of uses of crop mixtures, undersown crop, or winter catch crop used in the last 5 years of rotation), (4) 'rotation' (the number of cultivations of cereals, grass-clover ley, or other crops in the last 5 years of rotation, and (5) 'harrowing' (the use of physical weed control in the surveyed spring cereal). Primary tillage was not included as a variable, because inversion tillage was the common primary tillage practice on all the farms involved in the survey.

6.3.3. Trait data

A trait database was compiled for the observed species. In total, 149 species were included (Table A1, Appendix A). Exceptions were made for species identified at the genus level for reasons of unidentifiable trait variance within the genus, as well as voluntary crops. Both these groups were excluded from the species list. The trait database was based on the database of Bàrberi et al. (2018) and expanded further to include species found during the monitoring, but not previously listed (Table A2, Appendix A; includes sources). The traits included in the analysis were chosen specifically for our research objectives, which were Raunkiaer life form (RLF), growth form (GTF), Grime's life strategy (GLS), specific leaf area (cm^2 g^{-1}) (SLA), plant height (m) (PLH), seed weight (mg) (SWT), duration of flowering period (months) (DFF), seasonality of germination (SSG), and affinity to soil nutrient conditions (SNC). Detailed traits descriptions can be found in Table A2 (Appendix A).

6.3.4. Data analysis

A multivariate analysis of the weed species composition was performed to study the dispersal of species and sites. The weed species records were used as presence/absence data for the multivariate analysis, as the large variation of species density data caused extreme and uninterpretable ordination patterns. A correspondence analysis (CA) (ter Braak, 1986) was performed on the whole dataset, and the resulting ordination plot displayed sites and species dispersal.

The relationships between region and traits and between crop management and traits were studied by means of a RLQ method, which addresses the fourth-corner problem (Dolédec et al., 1996; Dray and Legendre, 2008). This analysis was performed on the basis of three datasets. The first was the so-called R-table, which consists of 'environmental' or, in our case, management data per field. The second was the L-table, which contains the density data of each species for each field. The third was the Q-table, which contains the trait data for each species. The analysis combines several multivariate techniques in order to relate the species traits to the management or environment data.

The three datasets were first analyzed through the use of ordination methods. This meant a CA for the L table and a Hill-Smith ordination for the Q and R tables (Hill and Smith, 1976). The results from these ordinations were used for the RLQ analysis. The relationships between the management variables and the traits were then tested by means of a fourth-corner analysis (Dray and Legendre, 2008). To test the crop management variables more closely, a backward selection was made, excluding the traits which had no significant correlation with management variables. Qualitative traits were tested on all levels but showed no significant relationships. Therefore, the following traits were entered as qualitative, and interpreted from the functional group analysis: RLF, GTF, GLS, SSG, and SNC. Associations between two categorical variables were tested with Pearson chi-square statistics (X^2), associations between a categorical variable and a continuous variable were tested using a pseudo-F and Pearson's r correlation ratio, and associations between two continuous variables were tested using a Pearson correlation coefficient.

Following the fourth-corner analysis, biplots for the management and trait data were compiled, which, after the species distribution on the basis of management variables and traits, were plotted in the ordination space. The functional groups were identified using the hierarchical cluster analysis, using Ward's method based on the Euclidean distances, for more detailed interpretation of the underlying dynamics. The functional groups were observed to further understand the interactive mechanisms of the management and trait variables. All the statistical analyses were performed with R software version 3.5.1 (R Core Team, 2017), utilizing the ade4 package (Dray and Dufour, 2007).

6.4 Results

6.4.1. Region interactions with traits in the weed community

The ordination plot of the CA performed on the weed communities demonstrated a clear geographical clustering (Figure 1). The full species list is available in Table A1 (Appendix A). According to their individual weed communities, fields within a region were visibly similar and clustered in a north-to-south orientation. In contrast, Latvia deviated from this picture by settling into its own cluster. This clustering reflected the regionally diverse environmental factors, which in turn created a weed community that was regionally distinct.

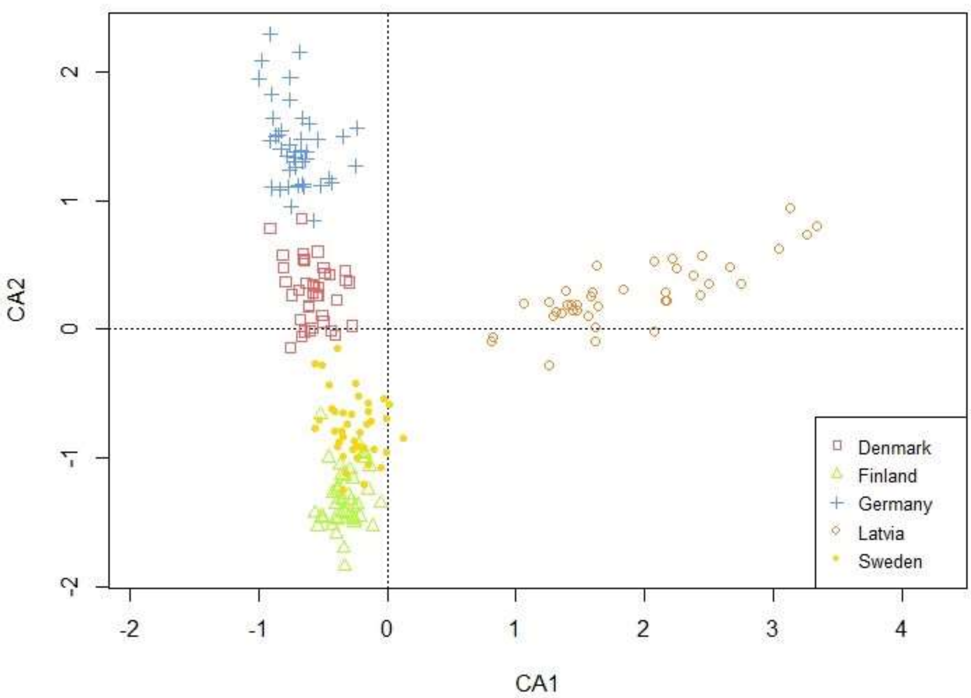


Figure 1. Projection of the 207 fields on the first two principle axis from the correspondence analysis (CA). Symbols display the five surveyed regions.

The only weed trait regions selected for was Raunkiaer life form (RLF), and it specifically discriminated Latvia (Table 1). Latvia as a region selects for perennial species, specifically for geophytes (plants with underground storage organs) and chamaephytes (dwarf shrubs). When the data from Latvia were tested on their own (data not shown), we found tendencies that perennial species positively correlated with crop and pre-crop ($X^2 = 0.366$ and $X^2 = 0.322$, respectively) and negatively correlated with the use of winter catch crops and other crops (other than cereals, grass, or clover ley) in the rotation ($X^2 = 0.242$ and $X^2 = 0.245$, respectively). The other traits and regions had no relationships.

Table 1. Relationships between weed traits and region variables represented by the adjusted p-values from the fourth corner analysis.

Region	RLF	GTF	GLS	SLA	PLH	SWT	SSG	DFF	SNC
Denmark									
Finland									
Germany									
Latvia	X^2: 0.0075								
Sweden									
Region general	X^2: 0.036								

Empty boxes represent not significant values. Raunkiaer life form (RLF), Growth form (GTF), Grime's life strategy (GLS), Specific leaf area (SLA), Plant height (PLH), Seed weight (SWT), Duration of flowering period (DFF), Seasonality of germination (SSG) and Affinity to soil nutrient conditions (SNC). Associations between two categorical variables were tested with a Pearson chi-square statistics (X^2).

Table 2. Relationships between weed traits and crop management variables represented by the adjusted P-values from the fourth-corner analysis.

Crop management variables		RLF	GTF	GLS	SLA	PLH	SWT	DFF	SSG	SNC
Crop	Cereal			-0.365						
	Cereal intercropped									
	Cereal undersown			0.265						
Crop general				0.355						
Previous crop	Cereal									0.263
	Grass Clover									
	Row crop									
	Summer crop						0.265			
	Winter Cereal									
Previous crop general										0.293
Crop diversity freq	Crop mixture									
	Undersown			**0.047**						
	Winter catch crop								-0.315	
Rotation freq	Cereal		0.293					**-0.047**		
	Grass Clover		-0.207					0.207		
	Other crop									
Harrowing	No		0.265			0.265				
	Yes		0.265			-0.265				
Harrowing general			0.285			0.293				

Empty boxes represent P > 0.4, bold values are P < 0.05. Raunkiaer life form (RLF), Growth form (GTF), Grime's life strategy (GLS), Specific leaf area (SLA), Plant height (PLH), Seed weight (SWT), Duration of flowering period (DFF), Seasonality of germination (SSG) and Affinity to soil nutrient conditions (SNC). Associations between two categorical variables were tested with a Pearson chi-square statistics (X^2).

X^2 = Pearson chi^2, two-sided P-value, except for generalized values

Pseudo-F and Pearson's r correlation ratio, two-sided P-value

Pearson's correlation coefficient, two-sided P-value

6.4.2. Crop management interactions with traits in the weed community

The subsequent analysis excluded the data from Latvia, as this region expressed a distinct trait selection on local level. The first two axes of the RLQ accounted for 46.8% and 21% of the total inertia (Figure 2). The Monte Carlo test indicated the relationships between traits and environment which were generally significant ($p < 0.05$, based on 9999 permutations). The first two axes of the RLQ showed relatively low correlations (23% and 20%, respectively), but the variance of the environmental scores was well preserved on the first two axes with 76%. The variance of the traits scores on the first two axes was up to 84%.

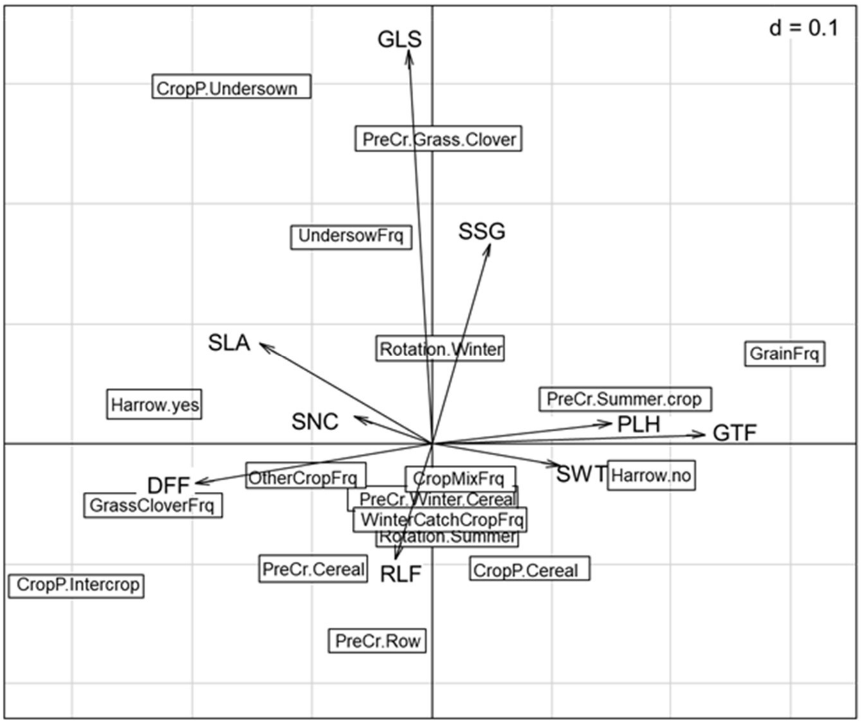


Figure 2. Biplot representing traits (arrows) and management (boxes) data. Traits: Raunkiaer life form (RLF), growth form (GTF), Grime's life strategy (GLS), specific leaf area (SLA), plant height (PLH), seed weight (SWT), duration of flowering period (DFF), seasonality of germination (SSG), and affinity to soil nutrient conditions (SNC). Management: harrowing (yes, no), crop present (cereal, intercrop, undersown), previous crop (cereal, grass clover, row crop, summer crop, winter crop), dominant seasonality of the crop rotation (summer, winter), crop diversity frequency in last 5 years (crop mixture, undersowing, winter catch crop), and rotation frequency in last 5 years (grain, grass clover, other crops).

According to the fourth-corner analysis (Table 2 and Figure 2), elements of the rotation in which spring cereals were cropped had the strongest interactions with weed traits. Undersowing was positively associated with Grime's life strategy, while the years of cereal in the rotation correlated negatively with duration of flowering. These significant results were followed by visible trends in the results (Table 2). Harrowing negatively impacted the plant height and selected for rosette forming species, reducing creeping or ascending species. The years of cereals or grass-clover ley selected differently for growth form, with cereals selecting for ascending and creeping species, while grass-clover ley selected for rosette species. Grass-clover ley was also associated with longer flowering periods. A pre-crop of spring cereals was positively associated with nitrophile species. When the present crop was pure cereals, these tended to select for species with a competitive life strategy. A present crop with undersown crops was associated positively with species with a more stress tolerant or diverse life strategy. Specific leaf area was not affected by any of the tested crop management variables; this is echoed in Figure 2, where this trait is positioned unattached of the other interactions. The number of years a field was under organic cropping was tested, but no trait selection was observed.

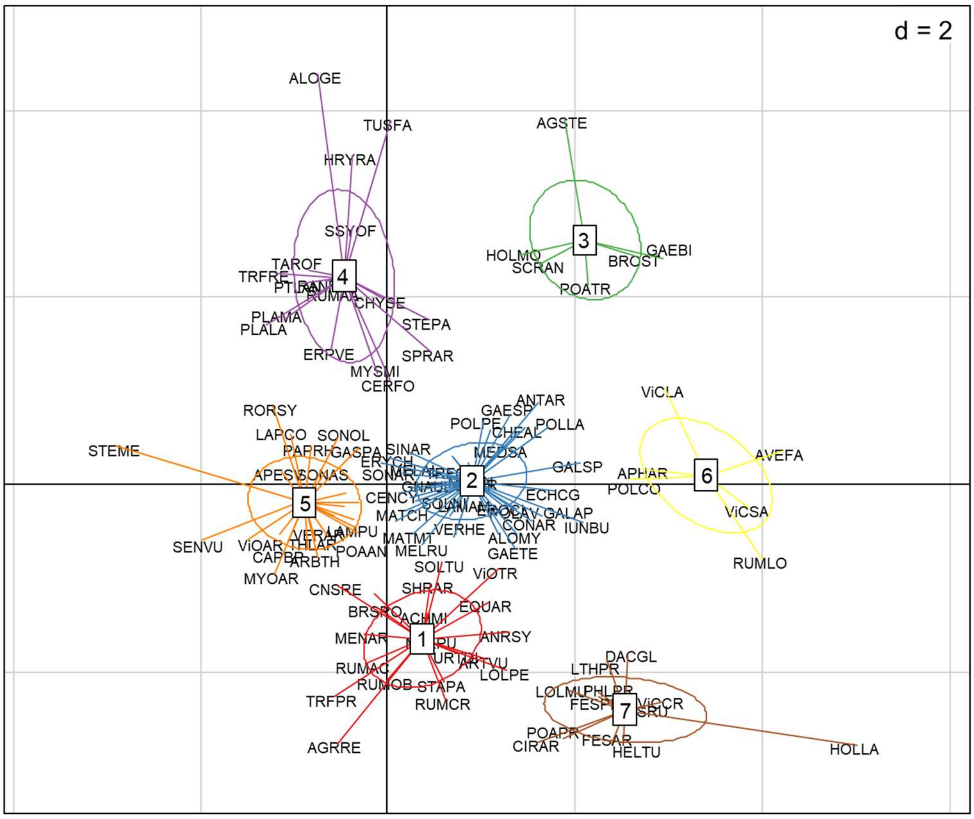
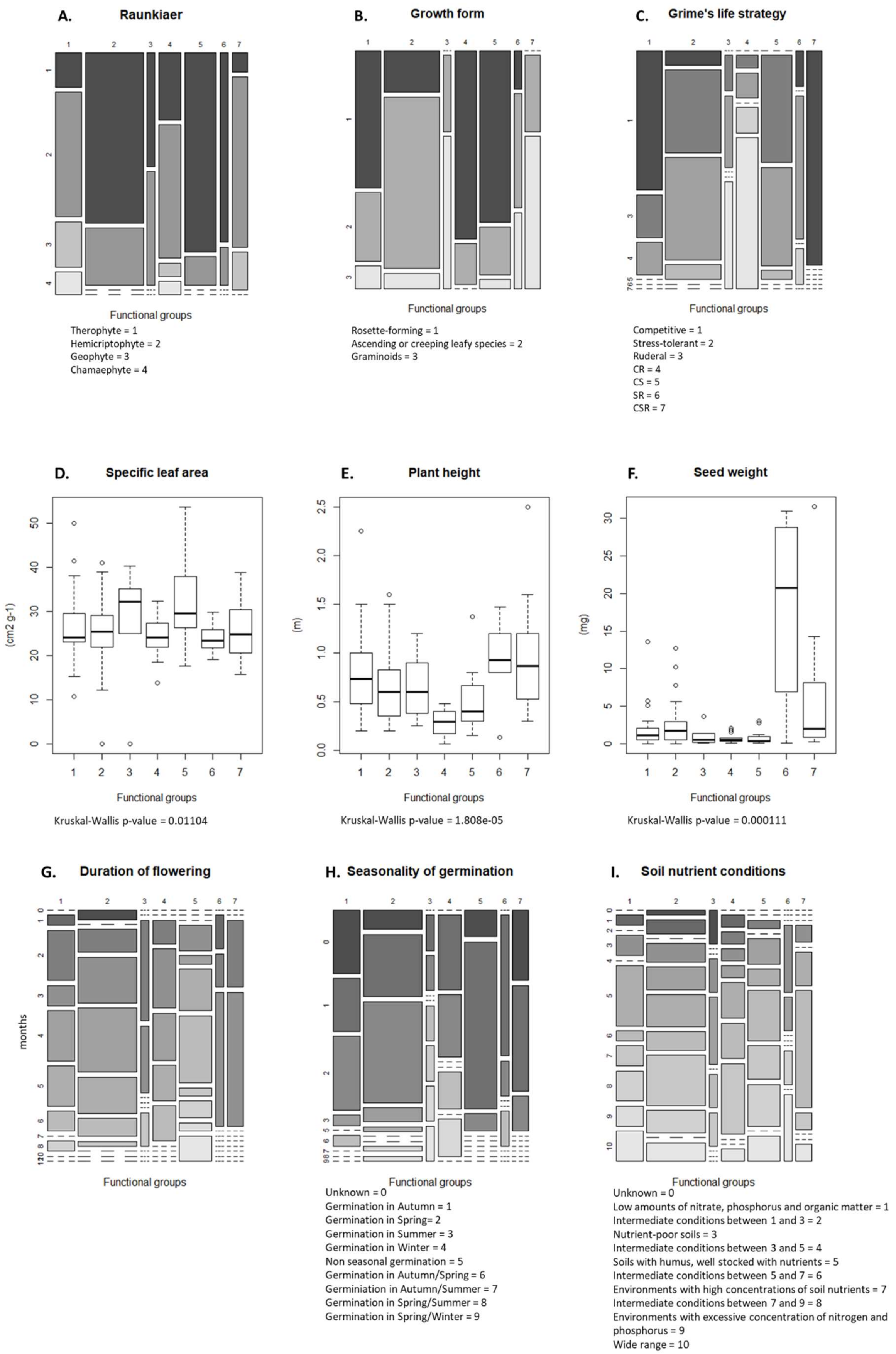


Figure 3. Ordination plot of species with functional group clusters along the first two RLQ axes. EPPO codes are used to indicate the weed species. Not all species are displayed for readability. Functional groups: (1) competitive perennials, (2) larger annuals, (3) annual grasses, (4) grassland perennials, (5) smaller rosette forming annuals, (6) big seeded annuals, and (7) perennial grasses.


A. Raunkiaer
Functional groups
Therophyte = 1
Hemicriptophyte = 2
Geophyte = 3
Chamaephyte = 4
B. Growth form
Functional groups
Rosette-forming = 1
Ascending or creeping leafy species = 2
Graminoids = 3
C. Grime's life strategy
Functional groups
Competitive = 1
Stress-tolerant = 2
Ruderal = 3
CR = 4
CS = 5
SR = 6
CSR = 7
D. Specific leaf area
(cm2 g-1)
Functional groups
Kruskal-Wallis p-value = 0.01104
E. Plant height
(m)
Functional groups
Kruskal-Wallis p-value = 1.808e-05
F. Seed weight
(mg)
Functional groups
Kruskal-Wallis p-value = 0.000111
G. Duration of flowering
months
Functional groups
H. Seasonality of germination
Functional groups
Unknown = 0
Germination in Autumn = 1
Germination in Spring= 2
Germination in Summer = 3
Germination in Winter = 4
Non seasonal germination = 5
Germination in Autumn/Spring = 6
Germiniation in Autumn/Summer = 7
Germination in Spring/Summer = 8
Germination in Spring/Winter = 9
I. Soil nutrient conditions
Functional groups
Unknown = 0
Low amounts of nitrate, phosphorus and organic matter = 1
Intermediate conditions between 1 and 3 = 2
Nutrient-poor soils = 3
Intermediate conditions between 3 and 5 = 4
Soils with humus, well stocked with nutrients = 5
Intermediate conditions between 5 and 7 = 6
Environments with high concentrations of soil nutrients = 7
Intermediate conditions between 7 and 9 = 8
Environments with excessive concentration of nitrogen and phosphorus = 9
Wide range = 10

Figures 4A-I. Distribution of trait values within the 7 functional groups. Boxplots are used to display continuous traits, while mosaic plots are used for categorical traits; in the case of duration of flowering, a mosaic plot was chosen too. Functional groups: (1) competitive perennials, (2) larg annuals, (3) annual grasses, (4) grassland perennials, (5) rosette forming annuals, (6) big seeded annuals, and (7) perennial grasses.

The cluster analysis identified seven functional groups (Figure 3). The distribution values of the nine traits of each of these groups are presented in Figure 4A–I. Group 1 was characterized by competitive perennials, group 2 was characterized by large annuals, group 3 consisted mostly of annual grasses, group 4 was composed of rosette forming perennials, which could be characterized as grassland species, group 5 included rosette forming autumnal annuals, group 6 specifically involved big-seeded annuals, and group 7 consisted of perennial grasses. When studying Figures 3 and 4 while observing Table 2, patterns emerge. Group 4, consisting of grassland species and characterized by a diversified life strategy, was correlated with the use of grass-clover ley and undersown crops. Groups 2 (larger annuals) and 6 (big seeded annuals) were positioned in the direction of growth form, seed weight, and plant height; however, it is less clear how these groups load in the absence of harrowing. Both groups had the same growth form composition and could both be influenced by the frequency of cereal and grass-clover ley in the rotation. The duration of flowering positively correlated with the use of grass-clover ley, and the group occurring on basis of this trait was group 5 (rosette-forming annuals with long flowering periods). Group 2 with large annuals occurred opposite and toward the cultivation of cereals in the rotation and displayed shorter flowering periods. Group 3, broadly consisting of annual grasses with indifferent or complex seasonal germination, positioned itself along the SSG axes and opposite the use of winter catch crops. Winter catch crops posed a selection pressure on species more clearly autumn- or spring-germinating. Group 1 and 7, large perennials and perennial grasses, showed no clear association according to their positioning. From the lack of interaction of crop management and the Raunkiaer trait, it is clear that annuals and perennials are not directly affected as traits by the crop management.

6.5 Discussion

Evident from the clear clustering (Figure 1) the weed communities found in this study were regionally specific and influenced by both the local climate and the soil conditions, as well as the local management. The finding that weed species compose locally unique weed communities is coherent with other studies on the effects of local soil type, altitude, and climatic conditions on weed species throughout Europe (Andersson and Milberg, 1998; Glemnitz et al., 2000; Hanzlik and Gerowitt, 2011; Lososová et al., 2004; Šilc et al., 2009). However, when analyzing, if region selected for certain traits, the results indicate limited influence (Table 1). With the Latvia region as the exception, we found our first hypothesis not supported. An accumulative effect of 'region' as a filter for trait selection has not been often investigated, although soil type, temperature, and precipitation have been studied by others (Fried et al., 2012; Lososová et al., 2004). Fried et al. (2008) stressed the weak effects of location, as subordinate to the stronger selection of crop choice and sowing date.

Although we conducted the study within spring cereals solely, meaning one crop type and spring sowing, the filter of region was still minor. The Raunkiaer trait selection in Latvia toward hemicryptophytes and geophytes weed species, locally presented in high densities of *Elytrigia repens* (L.) Nevski, *Equisetum arvense* L., and *Taraxacum officinale* F. H. Wigg., could be explained by the relative high use of undersowing, ley farming, and fodder crops. These different choices in management reduce the incidences of (soil) disturbance, favoring perennial species(Andreasen and Stryhn, 2008; Armengot et al., 2016). The ordination plot based on the weed species of all sites (Figure 1) revealed that the species composition was very different and specific for each region. Together with the weak selection for traits, this suggests that, although the weed communities were different in species composition, they served the same set of traits. Hence, the regional species pool providing different species with similar traits allows other species in each region to use the opportunities provided by spring cereal fields. Another explanation for the minor differences in traits could be the limited traits geared toward geography, such as latitude and temperature, which were not included in the analysis (Glemnitz et al., 2000; Lososová et al., 2004).

The crop management variables on undersowing and cereal frequency in the rotation were found to affect weed traits (Table 2), confirming our second hypothesis. The undersowing frequency connected with Grime's life strategies selected for weed species with a more diverse strategy. As shown in Figure 4, group 4 consists mostly of species which combined all three strategies (competitive, stress-tolerant, and ruderal). The repetitive undersowing of legumes and grasses selected for species which can deal with the additional competition, not through 'competitiveness' per se, but by being adaptable. Gunton et al. (2011) found an interaction of the Grime's life strategy trait with the crop architecture, where single-stemmed or open-rosette crops selected for more competitive species, showing the opposite movement. The dominance of cereals in the previous years of the rotation selected for species with shorter periods of flowering. However, general cereal cropping in the agronomic context of this study was based on spring sowing varieties (4:1 ratio for spring–autumn in our data), thus pushing for weeds with a shorter flowering period by spring tillage (Smith, 2006) and sowing date (Fried et al., 2012; Gunton et al., 2011).

The functional groups found in Figures 3 and 4 reflected the minor crop management influences and, thus, formed recognizable functional weed groups primarily on the basis of their inherent traits. These groups reflected a rather ordinary organic spring cereal community behavior. The argument has been made before that organic management recreates the arable conditions for this diversity of weed species, allowing them to resettle in the specific niches for the specialist flora selected for by the agronomic constrains (Vigueira et al., 2013). No trait selection was found by the number of years under organic production. This is remarkable as the literature has discussed the selection for perennial species under organic management, especially in the Nordic regions (Albrecht, 2005; Rydberg and Milberg, 2000; Salonen et al., 2011; Turner et al., 2007). However, most of these studies were in comparison to conventional management, and it appears from our results that this selection might be initial and does not persist over time. The selection for perennial traits observed by previous studies could have taken place within the first few years of organic cropping. Melander et al. (2016) observed that it took 4–5 years of organic farming to build up a perennial weed problem, hinting at early establishment, although it could take up to 9–10 years in some sites. Hofmeijer et al. (2021) found an increase in species numbers and diversity under organic management over time. Hence, the allocation of weed species reflects the regional species pool but is not trait-related.

The low trait selection in this study might be due to the organic management in general. Needless to say, species numbers in organic arable farming are consistently higher than under conventional management (Armengot et al., 2012; Hald, 1999; Hyvönen et al., 2003; Roschewitz et al., 2005). Richness in the species pool increases the functional redundancy of the weed community (Fonseca and Ganade, 2001), i.e., multiple species are able to play equivalent roles, presenting similar functional and physical traits. Multiple species filling functional groups can be assumed to react to agronomical management or other environmental filters. The lack of regional selection for traits supports that even though communities consist of different species, the same traits are fully covered in the agronomical niches.

We see our hypothesis further explored in the recent literature, although for the inverse effect. Studies looking into the intensification of agricultural practices have demonstrated a decrease in weed diversity (Henckel et al., 2015), number of species (Munoz et al., 2020), and, ultimately, functional redundancy (Carmona et al., 2020; Laliberté et al., 2010). Together, these declines could lead to loss of resilience. Organic agriculture is arguably less intensive than conventional, lacking the addition of herbicides and inorganic fertilizers, while also being strong weed species filters. In our study, we observed the reverse effect on the clearly observed increase in species diversity (Hofmeijer et al., 2021). This could mean a higher level of functional redundancy. Hence, organic management could support a certain agility within the weed community against selection of species and could be additionally considered to buffer rather than filter weed traits.

6.6 Conclusions

The lack of regional trait selection provides insight in the behavior of different weed species within similar agricultural niches, where the exception of Latvia diverts back to the influence of management rather than location. The observed trait selection by crop diversity and the general effects of organic management found in this study are promising for the approach that weed diversity is able to mitigate the dominance of deleterious species (Melander et al., 2020, 2005; Storkey and Neve, 2018). Generally, smart and diverse implementation of crop management could stimulate a diverse weed flora, which in turn can form a manageable arable weed community. Additionally, the discussed inverse effect of the implementation of less intense or organic management indicates potential for the prevention of species losses, ecosystem service provision, and mitigation of systemic disturbances, such as changes in agricultural management or environmental factors. Hence, this potential buffering effect requires further exploration.

6.7 Acknowledgments

The authors would like to thank all the participating farmers, stakeholders, and students for their facilitating role in this study. The authors also thank Friederike de Mol for her statistical advice.

6.A Appendix

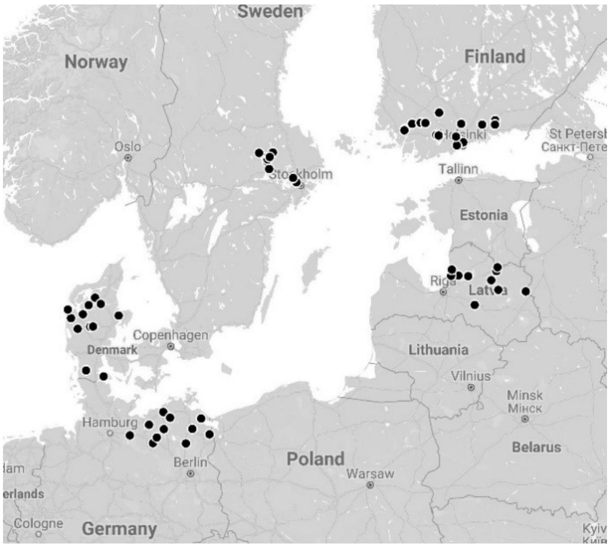


Figure A1. Location of the organic farms monitored in Germany, Denmark, Sweden, Finland, and Latvia. Published as Figure 1 in Hofmeijer et al. (2021).

Table A1. Species found in the monitoring and their relative frequency.

EPPO	Latin name	Frequency	EPPO	Latin name	Frequency
STEME	*Stellaria media* (L.) Cirillo	0,903	GNAUL	*Gnaphalium uliginosum* L.	0,043
VIOAR	*Viola arvensis* Murray	0,860	CMPRA	*Campanula rapunculoides* L.	0,039
CIRAR	*Cirsium arvense* (L.) Scop.	0,850	GASPA	*Galinsoga parviflora* Cav.	0,039

MATIN	*Tripleurospermum inodorum* (L.) Sch. Bip.	0,841	GERMO	*Geranium molle* L.	0,039
CHEAL	*Chenopodium album* L.	0,778	HORVX	*Hordeum vulgare* L.	0,039
MYOAR	*Myosotis arvensis* (L.) Hill	0,734	AEOPO	*Aegopodium podagraria* L.	0,034
AGRRE	*Elytrigia repens* (L.) Nevski	0,720	LOLSS	*Lolium* L. sp	0,034
POLAV	*Polygonum aviculare subsp. aviculare* L.	0,662	LTHSS	*Lathyrus* L. sp	0,034
POLCO	*Fallopia convolvulus* (L.) Å. Löve	0,652	SENVU	*Senecio vulgaris* L.	0,034
CAPBP	*Capsella bursa-pastoris* (L.) Medik.	0,594	SSYOF	*Sisymbrium officinale* (L.) Scop.	0,034
SPRAR	*Spergula arvensis* L.	0,551	TRFPR	*Trifolium pratense* L.	0,034
FUMOF	*Fumaria officinalis* L.	0,531	ANRSY	*Anthriscus sylvestris* (L.) Hoffm.	0,029
TAROF	*Taraxacum sect. Taraxacum* F. H. Wigg.	0,512	CHYSE	*Glebionis segetum* (L.) Fourr.	0,029
LAMPU	*Lamium purpureum* L.	0,507	DECCA	*Deschampsia cespitosa* (L.) P. Beauv.	0,029
EQUAR	*Equisetum arvense* L.	0,478	LOLMU	*Lolium multiflorum* Lam.	0,029
LAPCO	*Lapsana communis* L.	0,454	MEDLU	*Medicago lupulina* L.	0,029
THLAR	*Thlaspi arvense* L.	0,454	SCRAN	*Scleranthus annuus* L.	0,029
SONAR	*Sonchus arvensis* L.	0,396	AGSTE	*Agrostis capillaris* L.	0,024
LYCAR	*Lycopsis arvensis* L.	0,372	DAUCA	*Daucus carota* L.	0,024
POLPE	*Persicaria maculosa x minor*	0,367	PLALA	*Plantago lanceolata* L.	0,024
GAESS	*Galeopsis* L.	0,348	RUMOB	*Rumex obtusifolius* L.	0,024
VICSS	*Vicia* L. sp	0,314	ALCVU	*Alchemilla xanthochlora* Rothm.	0,019
ERYCH	*Erysimum cheiranthoides* L.	0,300	ATXPA	*Atriplex patula* L.	0,019
TRFRE	*Trifolium repens* L.	0,300	FESSS	*Festuca* L. sp	0,019
VICCR	*Vicia cracca* L.	0,295	HYPSS	*Hypericum* L. sp	0,019
CENCY	*Cyanus segetum* Hill	0,285	LUPSS	*Lupinus* L. sp	0,019
VERAR	*Veronica arvensis* L.	0,280	MEDSS	*Medicago* L. sp	0,019
RUMCR	*Rumex crispus* L.	0,266	RUMAC	*Rumex acetosa* L.	0,019
GALAL	*Galium album* Mill.	0,261	SHRAR	*Sherardia arvensis* L.	0,019
EROCI	*Erodium cicutarium* (L.) L'Hér.	0,256	ACHPT	*Achillea ptarmica* L.	0,014
GALSP	*Galium spurium* L.	0,256	ALOMY	*Alopecurus myosuroides* Huds.	0,014
VERPE	*Veronica persica* Poir.	0,256	ARBTH	*Arabidopsis thaliana* (L.) Heynh.	0,014
POLLA	*Persicaria lapathifolia* (L.) Delarbre s. l.	0,246	AVEFA	*Avena fatua* L.	0,014
ACHMI	*Achillea millefolium* L.	0,242	BRASS	*Brachiaria* (Trin.) Griseb. sp	0,014
POAAN	*Ochlopoa annua* (L.) H. Scholz	0,237	CENJA	*Centaurea jacea* L.	0,014
RANRE	*Ranunculus repens* L.	0,237	ERYSS	*Erysimum* L. sp	0,014
VICHI	*Vicia hirsuta* (L.) Gray	0,237	FESPR	*Schedonorus pratensis* (Huds.) P. Beauv.	0,014
ARTVU	*Artemisia vulgaris* L.	0,222	GAETE	*Galeopsis tetrahit*	0,014
TRFSS	*Trifolium* L. sp	0,222	GASCI	*Galinsoga quadriradiata* Ruiz & Pav.	0,014
CONAR	*Convolvulus arvensis* L.	0,217	MYSMI	*Myosurus minimus* L.	0,014
GERPU	*Geranium pusillum* L.	0,217	POAPR	*Poa pratensis* L.	0,014
RAPRA	*Raphanus raphanistrum* L.	0,217	VERSS	*Veronica* L. sp	0,014
SINAR	*Sinapis arvensis* L.	0,217	VIOTR	*Viola tricolor* L.	0,014
TUSFA	*Tussilago farfara* L.	0,217	ALOGE	*Alopecurus geniculatus* L.	0,010
GAESP	*Galeopsis speciosa* Mill.	0,213	APHAR	*Aphanes arvensis* L.	0,010
GALAP	*Galium aparine* L.	0,203	BROST	*Anisantha sterilis* (L.) Nevski	0,010
PAPRH	*Papaver rhoeas* L.	0,184	CERFO	*Cerastium fontanum* Baumg.	0,010
CVPCA	*Crepis capillaris* (L.) Wallr.	0,164	CIRVU	*Cirsium vulgare* (Savi) Ten.	0,010

LAMAM	*Lamium amplexicaule* L.	0,164	DACGL	*Dactylis glomerata* L.	0,010
MATMT	*Matricaria discoidea* DC.	0,159	FESRU	*Festuca rubra* L.	0,010
PLAMA	*Plantago major* L.	0,155	IUNBU	*Juncus bufonius* L.	0,010
SONAS	*Sonchus asper* (L.) Hill	0,155	MEDSA	*Medicago sativa* L.	0,010
MENAR	*Mentha arvensis* L.	0,150	MELAL	*Silene latifolia* Poir.	0,010
LOTSS	*Lotus* L. sp	0,145	POATR	*Poa trivialis* L.	0,010
PHLPR	*Phleum pratense* L.	0,145	RANSS	*Ranunculus* L. sp	0,010
STAPA	*Stachys palustris* L.	0,140	TRFCA	*Trifolium campestre* Schreb.	0,010
EPHHE	*Euphorbia helioscopia* L.	0,130	URTDI	*Urtica dioica* L.	0,010
RUMSS	*Rumex* L. sp	0,130	ALOSS	*Alopecurus* sp	0,005
CHESS	*Chenopodium* L. sp	0,126	BARVU	*Barbarea vulgaris* R. Br.	0,005
PTLAN	*Argentina anserina* (L.) Rydb.	0,126	BORSS	*Borago* L. sp	0,005
EPHES	*Euphorbia esula* L.	0,121	CNSRE	*Consolida regalis* Gray	0,005
GAEBI	*Galeopsis bifida* Boenn.	0,121	CONSS	*Convolvulus* L. sp	0,005
PLAME	*Plantago media* L.	0,121	CRDSS	*Arabidopsis* Heynh. sp	0,005
BARSS	*Barbarea* W. T. Aiton sp.	0,116	CRUCR	*Carduus crispus* L.	0,005
BRSRO	*Brassica rapa subsp. oleifera* (DC.) Metzg.	0,116	ECHCG	*Echinochloa crus-galli* (L.) P. Beauv.	0,005
LOLPE	*Lolium perenne* L.	0,116	FESAR	*Schedonorus arundinaceus* (Schreb.) Dumort.	0,005
RUMAA	*Rumex acetosella subsp. acetosella* L.	0,116	HELTU	*Helianthus tuberosus* L.	0,005
SONSS	*Sonchus* L. sp	0,111	HERMZ	*Heracleum mantegazzianum* Sommier & Levier	0,005
CERAR	*Cerastium arvense* L.	0,106	HOLLA	*Holcus lanatus* L.	0,005
PRASS	*Persicaria* Mill. sp	0,106	HOLMO	*Holcus mollis* L.	0,005
EPHSS	*Euphorbia* L. sp	0,101	HRYRA	*Hypochaeris radicata* L.	0,005
ANTAR	*Anthemis arvensis* L.	0,097	LITAR	*Buglossoides arvensis* (L.) I. M. Johnst.	0,005
MATCH	*Matricaria chamomilla* L.	0,097	LIUUT	*Linum usitatissimum* L.	0,005
LAMSS	*Lamium* L. sp	0,087	MALPU	*Malva pusilla* Sm.	0,005
LTHPR	*Lathyrus pratensis* L.	0,087	MELRU	*Silene dioica* (L.) Clairv.	0,005
RUMLO	*Rumex longifolius* DC.	0,082	MEUAL	*Melilotus albus* Medik.	0,005
BRSNN	*Brassica napus* L.	0,077	PIBSA	*Pisum sativum* L. *subsp. sativum*	0,005
PRUVU	*Prunella vulgaris* L.	0,077	PIEAB	*Picea abies* (L.) H. Karst.	0,005
SILSS	*Silene* L. sp	0,072	PLASS	*Plantago* L. sp	0,005
SONOL	*Sonchus oleraceus* L.	0,072	POASS	*Poa* L. sp	0,005
CHYLE	*Leucanthemum vulgare* (Vaill.) Lam.	0,068	RORSY	*Rorippa sylvestris* (L.) Besser	0,005
RUMCO	*Rumex conglomeratus* Murray	0,068	SETSS	*Setaria* P. Beauv. sp	0,005
RANAC	*Ranunculus acris* L.	0,063	SOLNI	*Solanum nigrum* L.	0,005
ERPVE	*Erophila verna* (L.) Chevall.	0,058	SOLTU	*Solanum tuberosum* L.	0,005
VERHE	*Veronica hederifolia* L.	0,058	SOOCA	*Solidago canadensis* L.	0,005
APESV	*Apera spica-venti* (L.) P. Beauv.	0,053	SSYSS	*Sisymbrium* L.	0,005
GERSS	*Geranium* L.	0,053	STASS	*Stachys* L. sp	0,005
VICSA	*Vicia sativa* L.	0,053	STEPA	*Stellaria palustris* Hoffm.	0,005
ARFTO	*Arctium tomentosum* Mill.	0,048	TRKMO	*Medicago sativa* L.	0,005
AMSSS	*Amsinckia* Lehm. sp	0,043	URTUR	*Urtica urens* L.	0,005
ANGAR	*Anagallis arvensis* L.	0,043	VESSS	*Verbascum* L. sp	0,005
BIDTR	*Bidens tripartitus* L.	0,043	VICLA	*Vicia lathyroides* L.	0,005
BRSRA	*Brassica rapa subsp. campestris* (L.) A. R. Clapham	0,043	VICVI	*Vicia villosa* Roth	0,005

Volunteer crops are removed from this list. EPPO codes (EPPO, 2021) and Latin names based on the Flora Europaea (EURO+MED, 2006).

Table A2. The nine functional traits included in the database.

Trait code	Source of information	Trait level /value	Trait explanation
1. Raunkiaer life form (RLF)	A, C, H	Qualitative; response and effect trait	The Raunkiær system (1934) is based on the place of the plant's growth point (bud) during seasons with adverse conditions (cold seasons, dry seasons)
			Therophytes: Annual plants which survive the unfavourable season in the form of seeds and complete their life cycle during favourable seasons; annual species are therophytes Hemicryptophytes: Buds at or near the soil surface Geophytes: Below ground - with resting buds lying either beneath the surface of the ground as a rhizome, bulb, corm, etc. Chamaephytes: Buds on persistent shoots near the ground – woody plants with perennating buds borne close to the ground, no more than 25 cm above the soil surface
		1.1	Therophyte = 1
		1.2	Hemicriptophyte = 2
		1.3	Geophyte = 3
		1.4	Chamaephyte = 4
2. Growth form (GTF)	A, C	Qualitative; response and effect trait	Species can be grouped into growth form classes based on their similarities in structure and function. Herbaceous species can be grouped into rosette-forming, ascending or creeping leafy species, and graminoids considering the architecture and occupancy of the space
			Rosette-forming: Cluster of leaves with very short internodes that are crowded together, normally on the soil surface but sometimes higher on the stem Ascending or creeping leafy stems: Growing uprightly, in an upward direction, heading in the direction of the top or growing along the ground and producing roots at intervals along surface Graminoids: Grass or grass-like plant, including grasses (Poaceae), sedges (Cyperaceae), rushes (Juncaceae)
		2.1	Rosette-forming = 1
		2.2	Ascending or creeping leafy species = 2
		2.3	Graminoids = 3
3. Grime's life strategy (GLS)	C, D, F, I	Qualitative; response and effect trait	Plants are classified according to their life strategy (Grime, 1974) (C as competitive, S as stress-tolerant, R as ruderal and the combined strategies CR, CS, SR and CSR). Despite some species can vary their strategy according to environmental and agronomic factors, their main life strategy is indicated For CSR strategy: for some species classes were attributed using the information available for similar species

		4.1	Competitive = 1
		4.2	Stress-tolerant = 2
		4.3	Ruderal = 3
		4.4	CR = 4
		4.5	CS = 5
		4.6	SR = 6
		4.7	CSR = 7
4. Specific leaf area (SLA)	H	Quantitative	SLA is a proxy for plant's ability to use light efficiently within the classical acquisition/conservation trade-off
5. Plant height (PLH) [m]	E, H, J	Quantitative	Plant height characterizes species ability to compete for light with neighbouring plants and especially with crop individuals
6. Seed weight (SWT) [mg]	D, G, J	Quantitative	Seed weight is related to species ability to disperse, colonise soil and persist
7. Seasonality of germination (SSG)	D	Qualitative; response and effect trait	Seed germination period determines the match between a weed species life cycle and the growing cycle of a crop hence its ability to escape disturbance posed by farming practices
		7.0	Unknown = 0
		7.1	Germination in Autumn = 1
		7.2	Germination in Spring= 2
		7.3	Germination in Summer = 3
		7.4	Germination in Winter = 4
		7.5	Non seasonal germination = 5
		7.6	Germination in Autumn/Spring = 6
		7.7	Germination in Autumn/Summer = 7
		7,8	Germination in Spring/Summer = 8
		7.9	Germination in Spring/Winter = 9
8. Duration of flowering period (DFF) [months]	C	Quantitative	Duration of the flowering period indicates the length of the reproduction phase. Mechanical removal of weed seeds before shedding is an excellent strategy preventing weed seeds from entering the seed bank. Duration of the flowering period also informs on the provision of floral resources for higher-trophic levels.
9. Affinity to soil nutrient conditions (SNC)	B	Semi-quantitative; response and effect trait	Species are classified on their affinity to soil nutrient conditions (N) following Ellenberg (1979) nutrient indicator values

	9.0	Unknown = 0
	9.1	Oligotrophic soils which contain low amounts of nitrate as well as
	9.2	phosphorus and organic matter = 1
	9.3	Intermediate conditions between a and c = 2
	9.4	Nutrient-poor soils = 3
	9.5	Intermediate conditions between c and e = 4
	9.6	Soils with humus, well stocked with nutrients = 5
	9.7	Intermediate conditions between e and g = 6
	9.8	Environments with high concentrations of soil nutrients = 7
	9.9	Intermediate conditions between g and i = 8
	9.10	Environments with excessive concentration of nitrogen and
		phosphorus = 9
		Wide range = 10

Sources of information: A: Pignatti, (1982); B: Ellenberg, (1979); C: Klotz et al., (2002); D: Fitter and Peat, (1994); E: Missouri botanical Garden, (2016); F: Grime et al., (2007); G: Kew Royal Botanical Gardens (2016, Kew); H: Kleyer et al., (2008); I: Hodgson, (2016). J: Westoby, (1998). Based, and extended, on the original database of Bàrberi et al. (2018).

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7 General discussion

In this chapter, the results from the previous chapters are discussed. The aim was to study the effects of crop diversity, such as undersowing, intercropping and winter catch crops, on weed density, diversity, the weed community, and if it selects any weed species traits. Next to this, the effects of direct control, which in study was harrowing, and crop management, in the form of the crop, and preceding crop, and years organic were studied. The chapter will be concluded with an outlook on weed science and crop diversity implementation in organic agriculture.

7.1 Crop diversity as affecting general weed density, diversity and communities

In the presented work the effects of crop diversity on weed communities were studied in multiple dimensions, from community level (Ch. 5) to species level (Ch. 6), and from regional scale (Ch. 4) to international scale (Ch. 5 & 6). This allowed for a deep and systemic exploration of the research aims.

The combination of presenting the analysis of a regional and international database made it possible to study the effects of arable management and crop diversity with and without the prominent effect of multiple environments. The regional data (Ch. 4) showed more detailed interactions with specific weed species, and stronger effects for grass-clover leys, winter catch crops and other crops than cereals or leys. Although other regions were not represented individually, we can expect locally distinct effects, based on the different environments, farming systems, use of crop diversity, and local species pool. When studying the combined international realm with the larger dataset (Ch. 5), we observe less detailed effects, however, the effect of the winter catch crops is displayed on both regional and international levels. The effect can be considered stronger or more uniform on this larger and more varied dataset, pushing through the 'noise' of the regions. The same effects are observed with years of organic management and harrowing, both observed in the German data set and internationally. The well documented effect of crop type present and previous crops on weed populations (Andreasen and Skovgaard, 2009; Fried et al., 2008; Hanzlik and Gerowitt, 2011), was observed in both levels too, although with different crops. It becomes clear these effects seem to be universal, this renders the winter catch crop and organic management effect notable as drivers for weed diversity.

One of the most pronounced observations were on the differences between direct control and crop diversity management. Although already thoroughly discussed in the respective chapters, the trends were similar between the regional and international database; direct measures such as harrowing and crops decrease densities, but not diversity, and systemic measures such as organic management and winter catch crops increase diversity, but do not affect densities. These two weed management practices concur with the direct short term measures and systemic and integrated long term cultural measures as discussed by Bàrberi (2002). As he explains in his paper, the effects that were found in this thesis could be the results of the different processes underlying the control measures. Direct physical weed control mostly focuses on covering and uprooting seedlings, and reducing the number of individuals. Preventative cultural measures, such as crop diversity, aim to reduce weed emergence by alternating winter and spring crops, or by utilizing niche-competing cover crops to prevent the establishment of specialized species.

Remaining areas of interest include: the effect of the accumulation of crop diversity measures, the interactions between measures, and clear rotational effects. Although rotation diversity and the seasonality of the rotation were tested during the analysis, it did not show statistically significant effects on the weed community. This is unusual as previous research observed effects of diverse crop rotation on weed communities (Lundkvist et al., 2008; Melander et al., 2020; Rasmussen et al., 2005; Ulber et al., 2009; Wortman et al., 2010). Critical reflection of what constitutes a 'low' or 'high' diverse crop sequence, and how to approach the rotation analysis with more depth, could be the next step to clarify how the past crop management might have further shaped the weed community over time. Studying the individual regions further would provide additional localized information on regional interactions.

In the multivariate analysis the most common species, like *Chenopodium album*, *Stellaria media* and *Viola arvense*, cluster centrally, in both regional and international analysis. These common weed species were not very reactive of environment and management, but seemed to have adopted a more generalist life strategy, highly adapted to the agro-ecosystem. It were the more rare or specialized weed species that reacted to changes in management, for example, *Silene spp* or grassland associated weed species like *Phleum pratense* and *Plantago media*. These showed the stronger relationships to environmental conditions, and were more responsive to crop management (Hanzlik and Gerowitt, 2011). The results did not show clear clustering in the multivariate analysis, however, some patterns in species were observed, such as the selection of mono species, clover and grassland-related species in grass-clover systems, and between winter catch crops and some small perennials. Additionally, all variables studied (i.e. years organic, crop present, preceding crop, weed harrowing, seasonal crop sequencing, undersown, crop mixtures, winter catch crops, grass clover, cereals, and other crops), presented significant effects (eigenvalues) on the community. Because the effects of the crop diversity variables were small compared to larger effects on the weed community, like 'crop present' and 'previous crop', patterns were hard to observe, but effects were measured non the less.

7.2 The effect of environmental and crop management factors on weed species and traits

The results of the multivariate analyses in chapter 4 and 5 suggested that crop management and diversity measures selected for certain species or species groups. The next step in chapter 6 was to explore the follow up hypothesis: crop diversity can select in favour or against certain weed traits. Even though some patterns were implied in the preceding analysis (Ch. 4 & 5), trait selection (Ch. 6) was evidently minimal and showed different patterns than in chapters 4 and 5. For example, although some perennial species were observed to load negatively on the use of winter catch crops in chapter 5, the use of this crop diversity did not result in trait selection against perennials in chapter 6. Winter catch crops did tend to select for unknown or spring germinating species, but this selection was weak. Although species did not load on undersowing in the ordination, nor did it affect weed density or diversity, the use of undersowing did display trait selection in favour of more diverse life strategies. The filling of niches and the more efficient use of resources can select against weeds with competitive traits. Furthermore, although rotation assembly (i.e. frequency of cultivating cereals) did not show strong effects on weed diversity or community, it did select for flowering traits. The results observed for organic management appeared to be similar to the winter catch crop results: species numbers increased, with no correlation to their traits. Similarly, the direct crop management variables that had an effect on densities and communities in chapter 5 showed no selection for traits. So, even though we observe an effect of crop diversity measures on trait selection, it does not necessarily reflect the effects on densities and diversity. Therefore, this filtering is not impacting numbers, nor the overall diversity.

When studying the weed species in the community as organized by their traits in chapter 6, patterns start to emerge in the form of functional groups. These functional groups display a trait distribution that is similar to classifications which are often informally mentioned in weed science, such as their response to the environment; 'segetal' species and 'grassland' species (Fried et al., 2016; Hyvönen et al., 2003; Munoz et al., 2020; Sattelmacher et al., 1987), or grouped by their functional traits; such as annual/perennial or spring/autumn emergence (Brandsæter et al., 2020; Bürger et al., 2020; Hofmeijer et al., 2019; Holzner and Glauninger, 2005). As observed in chapter 5 and discussed before, the most common weed species transcending regional effects (see 7.1), these functional groups are comprised of species which are highly adapted to the inherently disturbed agro-ecosystem (Storkey, 2006). Arable flora have traits that evolved in line with these disturbances, such as early seed set, high specific leaf area, quick germination, and long dormancies. These traits heighten their tolerance to filters in arable fields (Bourgeois et al., 2019), thereby allowing them to fill the niches that are consistently, but also occasionally, available in the agro-ecosystem. The species patterns found in chapter 3 and 6 are recognizable and echo each other. The species are arranged into groups based on similar problematic traits (Ch. 3), and the functional groups as organized by traits (Ch. 6). In chapter 3, the research aim was to find which weed species are considered 'problematic' or noxious, in order to have an understanding of which to aim for in control. In this chapter, we observe a few themes or groupings based on their 'problematic-ness', such as annuals with large biomass, species that utilise resources early in the season, and small common annuals with high fecundity. A weed group often mentioned as being problematic in organic literature are perennials (Brandsæter et al., 2011; Rasmussen et al., 2014; Salonen et al., 2011; Thomsen et al., 2015; Turner et al., 2007). Compared to the typical perennial grassland species, which are easier to control due to their sensitivity to tillage (Salonen and Ketoja, 2020), perennials with creeping rhizomes or roots, like *Elytrigia repens*, *Cirsium arvense,* and *Sonchus arvensis,* require more energy to control, particularly in arable fields. The 'functional' groups observed in chapter 3, were selected and based on different and more subjective traits, than the functional groups proposed by the analysis in chapter 6. However, it can be discussed that the 'problematic' groups are based on a collection of associated agronomically-driven traits. For example, the 'problematic' competitive annuals such as *Chenopodium album* are tall plants with competitive life strategies that allow them to compete for light, space and nutrients. Early annuals possess quick emergence traits and short duration of flowering. Whereas the 'problematic' perennials have tough and difficult to remove rhizomes.

In agronomy and weed sciences, weed species are continuously classified and collected in groups based on their traits. Agro-ecological niches are filled through environmentally-determined filtering effects on these traits. If there are multiple species that share certain traits, these species could substitute to fill these niches when comparable traits are selected for, also known as functional redundancy (Carmona et al., 2020). An example is the occurrence of *Fumaria* in Finland and Sweden, where it seems to fill a niche *Spergula arvensis* (or *Stellaria media*) fill in the more southern regions of this study. Both have overlapping traits, such as size, raunkiers life form, and soil nutrient requirements. Nevertheless, the environment in Sweden and Finland selects for *Fumaria officinalis* rather than *Spergula arvensis*, possibly based on other traits, like the 'season of germination,' and differences in flowering time. Hence, the practice of weed scientists to categorize species into trait-based groups, whether anthropocentric or otherwise, helps to understand field dynamics, and to target specific traits, niches and species groups with preventative control measures. A group of species that exploit the same class of environmental resources in a similar way, and show overlap in their niche requirements, are known in ecology as a 'guild' (Simberloff, 1991). A proposal could be made to utilise 'guilds' of weed species with a similar trait collection and which fill the same functional group in the agro-ecosystem. Categorizing weeds into 'guilds' could help understand the community dynamics in the field, especially when the shared traits in each guild can be linked to environmental conditions and management selection. These guilds could then be used as indicator species, for example for soil types (sandy, clay, or other), nitrogen conditions, or cropping history (winter or summer dominant, cereal or vegetable production, etc). Guilds could also support the ecological understanding of the present arable flora, with information on flower availability, soil cover and nitrogen fixation. Furthermore, categorising into guilds could support targeting potential problematic guilds like creeping perennials, with appropriate direct or cultural management.

7.3 Organic arable management as filter and buffer

Throughout this research, organic agriculture has been an interesting and noteworthy 'side effect'. In this study there is no comparison of the differences in effects between organic agriculture and conventional arable farming. Organic pest and disease management is characterised by its diverse nature, both in terms of space and time. Weed management in organic agriculture is generally more preventative than in conventional systems. In both diversity chapters (Ch. 4 & 5), an increase in species and diversity could be observed over time under organic management, in which new species are established in the community every 3-5 years. Starting with common arable species, followed by more rare species, species find their way back into the field, as organic management appears to create a favourable environment. Additionally, even though species number increase, organic management did not results in increased densities over a longer time span. This is a promising observation for organic agriculture, hinting at a stabilization of weed densities, and a more long term increase of arable plant diversity.

This increase in diversity can lead to improvements in ecosystem services and functioning (Clergue et al., 2009; Tilman et al., 2014), functional redundancy, and system resilience, as observed and described in chapter 6. As more species establish in the community, there are more opportunities for traits to be 'covered' and niches to be filled, even if one species is absent because of the environment created by the management implemented. This idea ties in to the guild proposal of the previous paragraph. The increased functional redundancy and species numbers means that multiple species share similar traits and are able to fill the same agronomical niche. Functional redundancy in itself implies the formation of groups based on individuals with similar traits. Thus, organic management could act as a buffer against the selection of traits, as discussed in chapter 6. Furthermore, as hypothesised previously by Carmona et al. (2020) and in chapter 6, organic management may extend this buffering potential towards other environmental impacts, such as disease spread (Ditzler et al 2021) and climatic events (Gallengher 2013, Pimiento 2020). Although in need of further research, these are promising hypotheses in light of the interest in increasing both resilience and sustainability in agroecological systems.

Even though it has been observed organic management increases and selects for perennial species (Albrecht, 2005; Rydberg and Milberg, 2000; Salonen et al., 2011; Turner et al., 2007), this selection or increase of perennials was not observed in the data. The selection observed in chapter 5 was not selecting in favour or against perennial traits. The increase in perennials observed in other studies can have taken place in the first few years of organic management, and, like densities, display early shifts in the weed community, but the buffering effect discussed in the previous paragraph could also explain some of the lack of selection. Nevertheless, creeping perennials will remain a cause for concern, and will mean continued control efforts for many organic farmers.

7.4 Outlook

7.4.1 Outlook for systemic approach in weed science

The initial hypothesis of this thesis was that the maintenance of a higher crop diversity prevents the development of a single weed specie, disrupt weed communities and thus could mitigate severe weed problems on the long run (Liebman et al., 2001; Melander et al., 2005; Storkey and Neve, 2018). This hypothesis was studied by identifying problem weeds, and study the effect of crop diversity on weed diversity and trait selection. It was found that crop diversity as well as organic management is increasing weed diversity. On top of that, we do not find selection for certain traits, showing that the crop diversity, and the diversity inherent to the organic management, is supporting a relatively stable and even trait community. Thus, the results from the presented research are considered a step closer to confirming the initial hypothesis. These results are promising in light of the decades of loss of floral diversity (Fried 2009; Storkey 2012), and the possibility to both invite and host rare species back in the field while improving weed management is exciting. The role of organic management, crop diversity, and subsequent weed diversity in the context of land-sharing debate could be further explored (Bourgeois et., 2020; Egan and Mortensen, 2012), especially if this diverse flora provides both ecosystem services and agricultural benefits. Also, an investigation of the effects of the interactions of increased crop diversity and more diverse and even weed communities on crop yields would be in line with the recent findings of Adeux (2019). Producing more insight in the processes behind and complex interactions between the crop development, arable management, and the functioning of weed communities, would help guide the application of specific crop diversity in arable farming.

7.4.2 Crop diversity as a weed control in organic agriculture.

As mentioned in literature before, there is no simple process to enhance weed diversity (Bàrberi, 2002; Bourgeois et al., 2020). This is an effect on system level and requires a diverse, ever changing, complex, holistic, system approach. This approach is fortunately intrinsic to organic agriculture, as an diverse and wide crop rotation is integral to prevent outbreaks of weeds, pest and diseases, especially to mitigate accumulation of soil born problems. Furthermore, organic operation are more often mixed farms adding animals grazing, fodder production and grass-clover leys to the management. A focus on soil organic matter accumulation and nitrogen fixation is adding motivation to the rotation complexity, and organic farmers tend to make more use of catch- and undersown crops (Askegaard et al., 2005) in order to have a more efficient nutrient and erosion management (Barbieri et al., 2017). The results in this research illustrate that this diverse organic approach also translates in weed species diversity. The presented results also show that the application of crop diversity is diverse and locally dependent, but if it was implemented it supports weed diversity. Crop diversity can further diversify the organic arable system, pushing for the diversification of the weed community, and support the preventative weed control approach. In order to control weed densities, harrowing and other direct management can be applied. This not only brings down numbers, and thus competition, but it also does not impede with weed diversity. A complex combined approach in weed management seems therefore suitable to keep densities in check and the weed community in a diverse shape. This is promising for farmers as these findings add to and strengthen the tools in their toolkit.

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Declaration of originality – Selbstständigkeitserklärung

With the following signature, I hereby declare that this thesis has been composed solely by myself and that I have not sought or used inadmissible help of third parties to produce this work. The contents of this work has not been submitted, in whole or in part, in any previous application for a degree, or professional qualification, at any other institution. All sources used to compose my work have been clearly referenced. Except where it is stated otherwise by reference or acknowledgment, the work presented is entirely my own.

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Ort, Datum	Unterschrift der Doktorandin

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