Inaugural dissertation
for
obtaining the doctoral degree
of the
Combined Faculty of Mathematics, Engineering and Natural Sciences
of the
Ruprecht - Karls - University
Heidelberg

Presented by

M.Sc. Laura Marie Kathrin Kellermann

born in: Munich, Germany
Oral examination: 24.05.2024

WORLD HUNGER VERSUS BIODIVERSITY

TRANSFORMATION APPROACHES TOWARDS A SUSTAINABLE AGRICULTURAL SYSTEM

Referees:	Prof. Dr. Marcus Koch PD Dr. Mike Thiv

The future is not a stroke of fate,

but the consequence of the decisions

that we make today.

[Franz Alt]

Abstract

Biodiversity loss threatens ecosystems worldwide through increasing habitat destruction, pollution and climate change, posing significant challenges to human well-being and ecological stability. As primary producers, plants form the foundation of ecosystems, sustaining countless life forms and providing essential ecosystem services such as carbon sequestration, soil stabilization and nutrient cycling. Plant biodiversity therefore holds immense potential for addressing these pressing global challenges. As agriculture accounts for around half of the total land area in Germany, it has great potential to mitigate many of the problems threatening the world's population. Especially nitrogen cycles and land use change, as well as the preservation of genetic and functional biodiversity, can be influenced by adapting the way in which land is farmed. Recognizing the opportunities offered by agriculture led to the implementation of the "Organic from Baden-Württemberg" action plan and also gave rise to the project AgroBioDiv as part of the Organic Farming research programme initiated by the state government in 2020. Within my study, I analysed how different forms of cultivation affect biodiversity in the arable landscape and how a transformation towards more sustainable, biodiverse agriculture can be guided and promoted. To this end, we carried out vegetation surveys of the arable weed flora on fields from organic farms, three farming communities practicing intermediate forms of agriculture, as well as purely conventionally farmed fields in 2021 and 2022. Based on the analysis of the species richness (Shannon Index) of the arable flora and the yield of the cultivated crops, I analysed the different cultivation methods comparatively, taking into account environmental parameters such as precipitation and temperature, location and soil conditions. The analyses revealed a significantly higher species diversity for organic cultivation compared to all other cultivation methods. However, even not organically certified fields, on which the use of chemicals was temporarily avoided, achieved significantly higher values than those on which pesticides were used. The strong influences of weather conditions, especially drought, and soil quality on weed biodiversity and yield emphasize the importance of climate-resilient crops. A much smaller influence on the number of species found on each field had the mechanical weed control and the study design influenced factors such as the height of the crop at the time of vegetation mapping.

My study contributes to a more holistic understanding of the complex dynamics shaping arable flora in Baden-Württemberg, providing a foundation for evidence-based conservation and land management strategies in the face of evolving environmental challenges. I propose to tailor specific protection measures to the unique needs of different landscapes and agricultural contexts within Baden-Württemberg to balance the imperative of ensuring food security and sustainability with the conservation of biodiversity and ecosystem resilience.

Zusammenfassung

Der Verlust der biologischen Vielfalt bedroht Ökosysteme weltweit durch die zunehmende Zerstörung von Lebensräumen, die Umweltverschmutzung und den Klimawandel und gefährdet damit das menschliche Wohlergehen und die ökologische Stabilität erheblich. Als Primärproduzenten bilden Pflanzen die Grundlage von Ökosystemen, auf ihnen basieren unzählige Lebensformen und sie erbringen wichtige Ökosystemleistungen wie Kohlenstoffbindung, Bodenstabilisierung und Nährstoffkreislauf. Die Pflanzenbiodiversität birgt daher ein immenses Potenzial für die Bewältigung dieser globalen Herausforderungen. Etwa die Hälfte der gesamten Landfläche in Deutschland wird landwirtschaftlich genutzt, sodass eine Anpassung der Bewirtschaftungsweise einen großen Einfluss haben, insbesondere auf Stickstoffkreisläufe und Landnutzungsänderungen sowie den Erhalt der genetischen und funktionalen Biodiversität. Diese Chance zu erkennen führte zur Implementierung des Aktionsplans "Bio aus Baden-Württemberg", aus dem auch das Projekt AgroBioDiv im Rahmen des von der Landesregierung initiierten Forschungsprogramms Ökologischer Landbau 2020 hervorging. Im Rahmen meiner Studie habe ich untersucht, wie sich unterschiedliche Bewirtschaftungsformen auf die Biodiversität in der Ackerlandschaft auswirken und wie ein Wandel hin zu einer nachhaltigeren, biodiversen Landwirtschaft begleitet und gefördert werden kann. Dazu haben wir 2021 und 2022 Vegetationsaufnahmen der Ackerbegleitflora von Biobetrieben, drei intermediär arbeitenden Anbaugemeinschaften, sowie auf rein konventionell bewirtschafteten Feldern durchgeführt. Basierend auf der Analyse des Artenreichtums (Shannon-Index) der Ackerbegleitflora und der Ertragshöhe der angebauten Nutzpflanzen habe ich unter Einbeziehung von Umweltparametern wie Niederschlag und Temperatur, Standort und Bodenbeschaffenheit die verschiedenen Anbaumethoden vergleichend untersucht. Der ökologische Anbau weist eine deutlich höhere Artenvielfalt auf als alle anderen Anbaumethoden. Aber auch nicht ökologisch zertifizierte Felder, auf denen vorübergehend auf den Einsatz von Chemikalien verzichtet wurde, erzielten deutlich höhere Werte als solche, auf denen Pestizide eingesetzt wurden. Die starken Einflüsse der Witterungsbedingungen, insbesondere der Trockenheit, und der Bodenqualität auf die Beikrautdiversität und den Ertrag unterstreichen die Bedeutung klimaresistenter Kulturen. Einen wesentlich geringeren Einfluss auf die Anzahl der auf den einzelnen Feldern gefundenen Arten hatten die mechanische Unkrautbekämpfung und das Studiendesign, das von Faktoren wie der Höhe der Kultur zum Zeitpunkt der Vegetationskartierung beeinflusst wurde.

Meine Studie trägt zu einem ganzheitlicheren Verständnis der komplexen Dynamik bei, welche die Ackerbegleitflora in Baden-Württemberg prägt, und bietet eine Grundlage für evidenzbasierte Schutz- und Landbewirtschaftungsstrategien angesichts der sich entwickelnden ökologischen Herausforderungen. Ich schlage vor, spezifische Schutzmaßnahmen auf die

besonderen Bedürfnisse der verschiedenen Landschaften und landwirtschaftlichen Kontexte in Baden-Württemberg zuzuschneiden, um die Notwendigkeit der Gewährleistung von Ernährungssicherheit und Nachhaltigkeit mit dem Erhalt der biologischen Vielfalt und der Widerstandsfähigkeit der Ökosysteme in Einklang zu bringen.

Table of Contents

1 Introduction

Nature never deceives us.
It is always we
that we deceive ourselves.

[Jean-Jaques Rousseau]

Nature provides us with everything we need to live, yet we treat it badly. At least 3.2 billion people's well-being is negatively impacted by human-caused land surface degradation (IPBES, 2018). This is driving the planet closer to a sixth mass species extinction and accounting for more than 10 % of the yearly global gross product in lost biodiversity and ecosystem services (IPBES, 2018).

Our ecosystem is closely interconnected and thus are the problems within. In their concept of planetary boundaries, Rockström et al. (2009) describe nine limits within which “humanity can continue to develop and thrive for generations to come”. Beyond these limits, the environment may not be able to self-regulate and therefore may not be stable anymore. The planetary boundaries as defined by Rockström et al. (2009) are climate change, ocean acidification, stratospheric ozone depletion, biogeochemical flows in the nitrogen cycle, global freshwater use, land system change, the erosion of biosphere integrity (= loss of biological diversity), chemical pollution and atmospheric aerosol loading. A recent study by Richardson et al. (2023) reviewed and updated the previous study and states, that not only three – as the calculations in 2009 suggested – but six boundaries have already surpassed the stable limit by far. Three of these are nitrate inputs into the soil, land system changes and the loss of biodiversity, all of which are closely linked to agricultural use and can be strongly influenced by the way in which land is managed. The close linkage of all components of our ecosystem (see Figure 1) triggers a whole

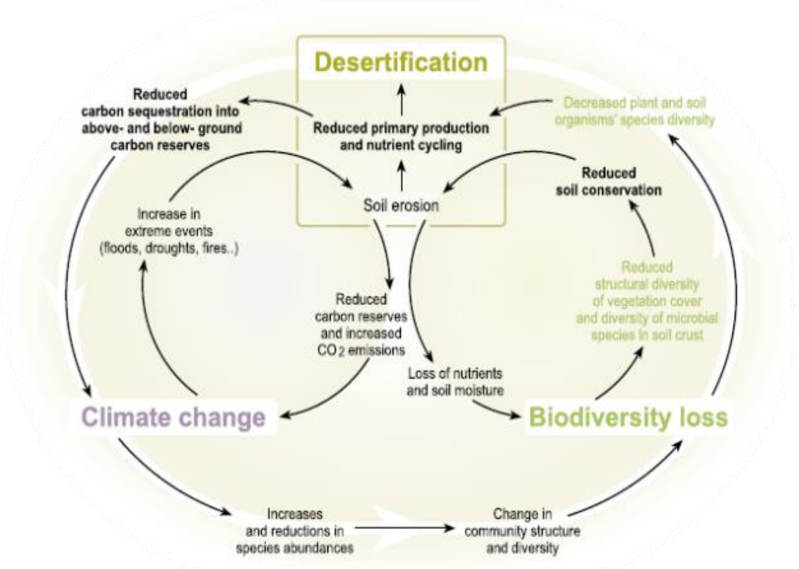

Figure 1: Linkages and feedback loops among desertification, climate and biodiversity. The major components of biodiversity loss (green) directly affect major dryland services (bold). Modified after (Eser, 2019)

chain of problems if only one element exacerbates. Just like a person who cannot live without lungs, even with a functioning heart, the earth can only keep us alive if all its vital systems are working. But this linkage also harbours opportunities to positively influence the whole ecosystem by even just small changes. This becomes clear with the example of global warming and species extinction: as much as the climate crisis is exacerbating the loss of biodiversity - what works best against global warming is functioning ecosystems that cool it down. This is the reason why species extinction should be taken just as seriously as climate change and species cannot be sacrificed for the sake of climate protection.

The intensification of agriculture is considered the biggest factor in biodiversity loss worldwide (Altieri & Nicholls, 2018; Fuchs & Schumacher, 2006). The biodiversity of arable weed plants has declined rapidly in recent decades, with far-reaching consequences for the entire ecosystem: An increase in monocultures, the use of synthetic pesticides, increased soil cultivation and the introduction of mineral fertilizers in particular have led to a genetic impoverishment of plant diversity (Albrecht et al., 2008). The issues are not unknown: Already in 1992, at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Germany adopted the Agenda 21 action programme and committed itself to protecting biodiversity (Ashida, 2014). In 2010, the Aichi Targets for the protection of biodiversity by 2020 were agreed internationally in Nagoya. But the 2019 report of the World Biodiversity Council IPBES provides a sobering result: none of the targets could be met (Díaz et al., 2019). Meanwhile, seed banks such as the Millenium Seed Bank in Wakehurst, England, hold over 2.4 billion seeds from all around the world, including more than 350 wild cereal species. If the destruction of our biodiversity continues as before, the hope is to be able to regain biodiversity through the conserved seeds (Breman et al., 2021). However, it would be much more expedient to protect what is left.

Characteristics of wild herbs in arable fields

More than a third of the established taxa in Baden-Württemberg are currently categorized as endangered, extinct or potentially endangered due to extreme rarity (Breunig & Demuth, 2023). This is a comparable level to 1999, but the endangerment situation for individual species has changed drastically. While heat- and drought-tolerant species in particular have stabilized, there has been a significant decline in species depending on nutrient-poor habitats, wetland biotopes, and especially in arable wild herbs (Breunig & Demuth, 2023).

Over thousands of years, arable wild herbs have developed together with the cultivated landscape. They are correspondingly well adapted to the form of cultivation in which they occur (Meyer & Leuschner, 2015). The typically annual plants have long-lived diaspores, an early flowering time, they produce large quantities of seeds and can often fruit several times per year. Most of the rare arable weeds are winter annuals that germinate in autumn, overwinter in the rosette stage and reach seed maturity by the time the grain is harvested (e.g. *Consolida regalis*, *Adonis aestivalis*). Other species only reach seed maturity after the grain harvest (e.g. *Kickxia* spec., *Stachys arvensis*) (Van Elsen et al., 2009). They form the basis of life for many insects, which are the food source for rodents, birds and other animals (Bengtsson et al., 2005), thus founding the source of a food web on which we humans ourselves depend. An average of twelve herbivorous and flower-visiting animal species depend on each arable weed species, which in turn feed a number of animal species (Dohrn, 2017). They are not only useful above ground: arable wild flora can play a significant role in improving soil health and fertility through various mechanisms. By accumulating organic matter through the decomposition of plant residues, soil structure and moisture retention are improved (Tsiafouli et al., 2015) and microbial diversity is enhanced (Eisenhauer et al., 2019). Diverse root systems of arable weeds create macropores in the soil, increasing water infiltration, aeration and root growth of subsequent crops. Weeds provide erosion protection for the crop, contribute to soil health, can fix nitrogen and support soil organisms. Many wild field herbs are used as medicinal or food plants, others are the ancestral form of today's cultivated plants. In addition, the richly flourishing fields can be useful as a marketing strategy for more biodiversity.

But besides all their advantages, arable wild herbs also compete for nutrients, space and water with the cultivated plants, can hinder their growth by shading them or be a mechanical disruptive factor, making field work more difficult (Walsh, 2019). In addition, some arable weeds act as host plants for fungi and pests. Therefore, arable weeds are not favoured by many farmers and often treated with pesticides, herbicides and fungicides, which might be the most drastic factor why their habitat is severely endangered. Besides chemical weed control, there are many other factors causing the sharp decline of the diversity on crop fields: increasingly intensive cultivation, seed cleaning, denser crop stands, early tillage, soil-improving measures such as fertilization and liming, or changes in the soil treatment such as significantly earlier stubble breaking, as well as the disappearance of old crops such as flax are making it increasingly difficult for wild herbs to continue to spread in their habitat (Breunig, 2002). This effect is accelerated by the fact that the few remaining areas where rare species in particular still occur are often far apart, which makes it difficult to advance into new areas or reclaim previously colonized areas. This especially affects species that were already rare in the past, as well as companions of old cultivated crops, low-growing wild herbs and those that depend on calcareous soil ("Kalkscherbenäcker") or highly acidic, nutrient-poor sandy soils. Moist indicators are also particularly threatened by the increasingly high temperatures. Once common wild herbs such as corn cockle (*Agrostemma githago*), lambs lettuce (*Arnoseris minima*), field delphinium (*Consolida regalis*), Venus ridge (*Legousia speculum-veneris*) and yellow goutweed (*Ajuga chamaepitys*) are hardly found nowadays (Breunig, 2002).

The biological state of the Heidelberg and Baden-Württemberg agricultural landscape

The state of arable companion plants in Baden-Württemberg has been analysed in a comprehensive study by Pierny (1994) thirty years ago. He carried out an assessment of the current state of development of arable flora in Baden-Württemberg as part of a regionalized concept of requirements and measures for its conservation, development and regeneration, as even then around a third of the species were endangered or extinct due to the intensification of agriculture, the use of herbicides, increased mineral fertilization, seed cleaning, etc. (Korneck & Sukopp, 1988). In his work, Pierny presented the potential, regionally typical arable flora in the individual parts of the landscape based on the prevailing site conditions and assessed the individual parts of the landscape with regard to their state of development on the basis of vegetation surveys. Finally, he drew up a catalogue of measures for arable extensification measures, which, in his opinion at the time, had to be carried out on 100 % of the area (Kaule, 1991). Thirty years later, however, there are also voices claiming the opposite: The special report "Climate Change and Land Systems" published by the Intergovernmental Panel on Climate Change (IPCC) in 2019 recommends intensifying agriculture in order to feed the world's population safely and sustainably (IPCC, 2019), although this argument implies that biodiversity in agroecosystems is functionally insignificant (Tscharntke et al., 2012a).

As recently as 2023, the Baden-Württemberg State Institute for the Environment (LUBW) published a new study in collaboration with the Institute for Botany and Landscape Studies in Karlsruhe, in which the arable flora throughout Baden-Württemberg was analysed on a large scale using representative study areas in order to determine recent populations of arable flora and propose specific protection and development measures. The results are alarming, as Schach et al. (2023) found: a substantial proportion of the arable weed flora in Baden-Württemberg is endangered. Only 62 of the 378 species recorded in the fields have a consistency of more than 10 %, for example, and some of the regions examined, such as the central Black Forest and the

Alpine foreland, showed a very low potential for current species diversity. Conservation measures have been successful for many grassland species, but the decline within the agricultural landscape is still enormous (Breunig & Demuth, 2023). In addition to the reasons already mentioned, the focus of arable use on high-yielding sites is also cited as a reason. Steeper slopes in particular have been taken out of use, resulting in permanent fallow land with scrub (Schach et al., 2023), where the specialized arable plants can no longer prevail against competition.

A similar picture of decreasing plant biodiversity emerged when Wörz and Thiv (2015) analysed the data from the floristic mapping of Baden-Württemberg (Wörz et al., 2024), in which floral records from as early as 1410 are available on a map-based platform for each individual species. They divided the data into three time intervals (before 1970, 1970-2004, from 2005 onwards) and found a persistent decrease in indigenous rare plant species with a simultaneous increase in neophytes. Although not only plants in agricultural environments were studied here, the authors also identify urbanisation, temperature increase and nitrogen inputs as the main causes of the decline.

Controversially discussed herbicides

Since the 1950s, yields per hectare of winter wheat, for example, have increased by 165 % (Bundesinformationszentrum Landwirtschaft, 2024). The harvest volume of winter wheat in Germany in 2022 was more than 22 million tonnes. To increase crop yields in the face of pests, farmers often use chemical fertilizers and pesticides, but at high cost for the environment. The German Environment Agency states restricting pesticide use as an important step to nature protection due to the negative environmental impacts: Pesticides can contaminate nearby biotopes, groundwater, and local waterways through unintentional further transport known as pesticide drift (Rosic et al., 2020). They also result in fauna impoverishment and habitat loss for birds and other animals living on farmlands. The German Environment Agency categorizes the loss of insect pollinators as an adverse impact of pesticides on biodiversity given the reduced occurrence of flowers on and near farmlands with pesticide application (UBA, 2021). However, the pollination of crops requiring insect-mediated pollen transfer is also severely affected, resulting in strong decreases in crop yield (Millard et al., 2021). In addition, some species have already developed resistance to herbicides; in German fields this is the case for 33 species (e.g. *Alopecurus myosuroides*, *Apera spica-venti*, *Lolium perenne* and *Matricaria chamomilla* (International herbicide-resistant weed database, 2022)). This is also problematic in view of the fact that rare and endangered species are unable to compete due to their small population size and low genetic flexibility. The impoverishment of biodiversity has also led to an increase in the occurrence of problematic weeds (Gerhards et al., 2013), as a result of which more than 25 % of the approximately 350 plant species found on arable land are currently on the Red List of vascular plants in Germany (Meyer & Leuschner, 2015).

To counter the problem of resistant problem weeds, many farmers resort to broad-spectrum herbicides. Glyphosate is the most controversially discussed and yet one of the most frequently used herbicides (Guyton et al., 2015). The active ingredient of many broad-spectrum herbicides affects a large proportion of arable weeds: it has an effect on higher plants and mosses, but also has undesirable effects on bacteria and fungi in the soil, which reduce soil quality (Zobiole et al., 2011). The toxicity of glyphosate to various organisms has been proven many times in studies, including e.g. insects, which are inevitably exposed to the herbicide in their habitat (Balbuena et al., 2015; Gill et al., 2018; Gregorc & Ellis, 2011). As it is also said to have negative effects on humans, for example as a potential carcinogen (IARC, 2017), a ban has been under discussion in Europe for years (Guyton et al., 2015). Although countless studies highlight the potential risks to a wide range of animal and plant species and despite several citizens' initiatives both at the EU-level and subnational-level in Germany calling on policy-makers to phase-out or reduce pesticide use in agriculture (Tosun & Varone, 2021), the EU countries did not take a joint position on whether to extend the authorization of glyphosate. Therefore, the EU Commission decided in December 2023 to allow Glyphosate usage until 2033.

The Action Plan "Organic from Baden-Württemberg"

Public awareness of the many serious problems associated with man-made issues such as climate change, intensive land use and biodiversity loss has risen sharply in recent years. More and more consumers want organically produced, regional products, little packaging waste and transparency. Steadily growing sales figures in natural food and food retailing show (AMI, 2022): the term "organic" is increasingly losing the bland aftertaste that accompanied it for a long time. Eventually, the demand for more species protection was also voiced in the society in Baden-Württemberg: The Biodiversity Strengthening Act ("Biodiversitätsstärkungsgesetz") was passed in July 2020 as a consequence of the "Save the Bees" referendum. As part of the sustainability strategies of the federal government and the state, the "Organic from Baden-Württemberg" action plan already supported the promotion of organic farming from 2011 to 2016. It was revised and reissued in February 2017 by the Ministry of Food, Rural Areas and

Consumer Protection Baden-Württemberg (MLR) and sets out a national strategy for the future of organic farming and aims to strengthen those who already farm organically as well as attract new players and involve everyone, including conventional farms. The Biodiversity Strengthening Act includes the expansion of organic farming and a reduction in the use of synthetic pesticides (MLR, 2020). In this way, the state aims to increase the proportion of ecologically managed land in Baden-Württemberg from only 13.2 % in 2019 to up to 30 % by 2030 (BMEL, 2023). According to the Baden-Württemberg State Statistical Office, in 2020, 4500 (11.3 %) of farms in Baden-Württemberg switched completely or partially to organic farming, which represents an overall increase of 46.9 % compared to 2010, with regional variation in number of farms and organically cultivated area (see Figure 2).

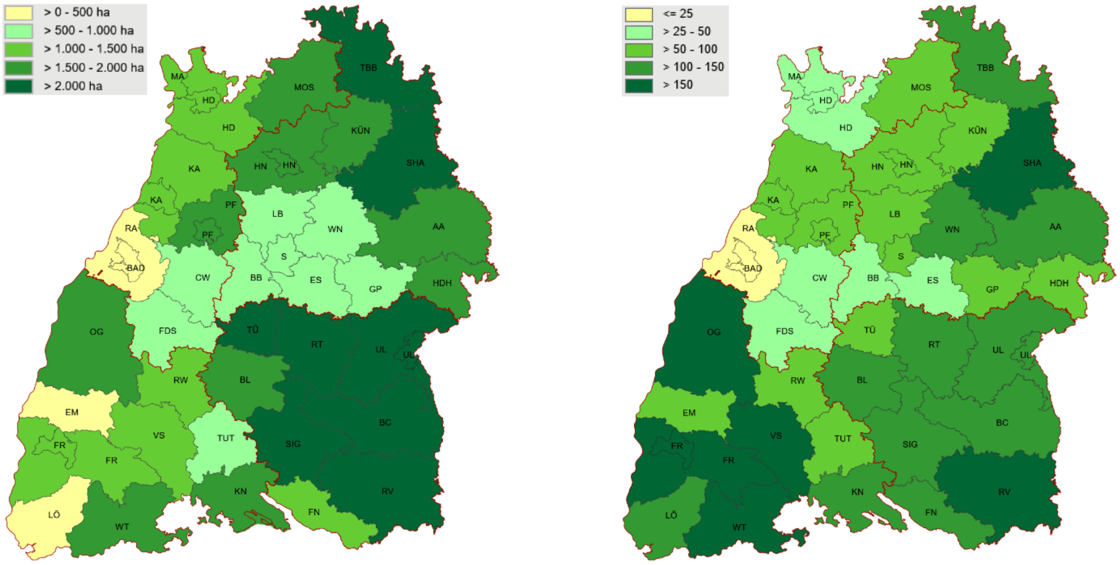

Figure 2: Organically cultivated area (A) and number of organic farms (B) in Baden-Württemberg 2018 (LEL, 2024)

If the positive trend continues at the same rate, it will increase to a share of 22 % in the year 2030. The implementation of the Action Plan is currently and again will be evaluated in 2027, the results of the 2023 evaluation will soon be published. With the help of a comprehensive catalogue of measures, the framework conditions for organic farms are to be improved and new entrants into organic farming and the organic food industry facilitated. Subsidized by structural funds amounting to 4.5 million euros annually, the action plan is divided into six fields of action. In the field of action "Production and Processing", one focus is the targeted further development of existing promotional offers, which include, for example, FAKT (Promotion Programme for Agri-environment, Climate Protection and Animal Welfare). Practice-oriented research and corresponding research funding should enable the further development of organic farming and create advisory and educational services. Furthermore, marketing structures (value creation, market position, supply) for organic products and their labelling in trade are to be improved. For quality assurance, control is also an important issue addressed by the action plan. This is to be ensured by strengthening the organic inspection authority, continuing the long-standing organic monitoring and formulating a new EU organic law. Finally, the issue of organic farming is to be brought into the focus of consumers through targeted public relations work (MLR, 2020).

One specific aspect of the “Organic from Baden-Württemberg” action plan was the implementation of the Organic Farming Research Network, consisting of four projects at different universities. AgroBioDiv, in the context of which I conducted my study, is one of them and is a joint research project of the Faculty of Political Sciences and the Faculty of Biosciences at Heidelberg University. A large amount of the data was collected in close cooperation between the two faculties and analysed from both the biological and political science perspectives. The results of the latter will be published after my thesis, but contribute to the overall understanding of the topic. In the second part of the discussion, I therefore move away from my vegetation data and place the themes of arable flora and climate-resilient agriculture in a global context.

The Federal Ministry of Food and Agriculture additionally launched an Organic Strategy 2030 in November in order to achieve the target of 30 % organic farming by 2030. It contains 30 measures with the aim of achieving sustainable, future-proof agriculture that is economically viable and at the same time does justice to the environment, animals and climate. The Organic Strategy 2030 aims to create suitable framework conditions along the entire value chain - i.e. from the provision of inputs to production and processing through to trade and consumption - and to remove existing obstacles so that 30 % of agricultural land in Germany can be farmed organically by 2030 (BMEL, 2023).

Organic farming as a solution approach for many challenges

Agriculture occupies about 38 % of the land surface all over the world, in Germany even half of the overall area (UBA, 2023). Since agriculture affects such a large proportion of the country's total area, sustainable farming practices have great potential to contribute to food security. Ecological or organic farming is a cultivation method that emphasizes the use of ecologically sustainable practices that intend to conserve biodiversity. Conventional farming produces up to 40 % more greenhouse gasses than organic farming, while organic farming systems use 45 % less energy than conventional systems, as shown by the Rodale Institute Farming Systems Trial, a long-term analysis of organic and conventional maize and soybean cropping systems (Hepperly et al., 2006). Results indicated an increase in soil organic matter (C_{org}) and N, providing multiple benefits to the overall sustainability of organic farming systems. High contents of C_{org} under organic management conserves nitrogen, leading not only to higher yields but also to increased protein levels. Crop rotations and cover cropping typical of organic agriculture reduce soil erosion, recycling of livestock wastes reduces pollution and abundant biomass both above and below ground increases biodiversity which helps in the biological control of pests and increases crop pollination by insects. Lastly, Hepperly et al. (2006) conclude that organic farming reduces greenhouse gases. According to the Intergovernmental Panel on Climate Change (IPCC, 2019), up to 12 % of global greenhouse gas emissions are contributed by agricultural land. The potential for widespread organic agriculture within this issue therefore is enormous.

The Thünen Report 65 (Sanders & Heß, 2019) summarizes 528 studies between 1990 and 2018 as part of a literature search to compare organic and conventional farming. They also come to the conclusion that organic farming has a high potential for protecting groundwater and surface water, especially for the input of nitrate and pesticides - on average, the nitrogen discharge is reduced by 28 % in the analysed studies. Organic farming also scores highly in terms of soil fertility: earthworm populations are up to 94 % higher on average, there is less acidification in the topsoil and soil penetration resistance (an indicator of soil compaction) is also 22 % lower. Furthermore, organic farming outperforms conventional farming in the areas of climate adaptation, nitrogen and energy efficiency (Sanders & Heß, 2019).

While there are many benefits for the environment, organic farming also comes with some potential disadvantages (Schaffer & Duvelmeyer, 2018). Implementing ecological farming practices may require the use of organic fertilizers, special equipment and labour-intensive practices. Managing pests and diseases can be more difficult, as ecological farmers dispense with chemicals. It therefore can be considered as more expensive and more time-consuming. The products may be difficult to sell in conventional markets. The lack of demand can to some extent be explained by the higher product price. Those problems also lead to challenges in scaling up: lower yields and higher costs stand against the rising demands of a growing population. Therefore, transforming their farm to ecological practices requires detailed planning and knowledge to prevent these potential disadvantages from the beginning.

Is organic farming justifiable in the face of global food undersupply?

The benefits of organic farming are numerous. Nevertheless, one aspect must not be neglected, especially in view of famines and increasingly frequent crop failures around the world due to extreme weather events and droughts: the yield. Agriculture faces the challenge of feeding a growing population with approximately one billion people being chronically malnourished on the one hand and with rising demand for meat and high-calorie diets on the other hand, while simultaneously minimizing its global environmental impact (Foley et al., 2011; Seufert et al., 2012). The situation is exacerbated by a robust negative association between warming and both caloric yield and cropping frequency: Zhu et al. (2022) predict a net global cropping frequency reduction (−4.2 ± 2.5% in high emission scenario) by 2050, suggesting that its climate-driven decline will exacerbate crop production loss and not provide climate adaptation alone. To feed the same amount of people at a lower crop yield rate, more agricultural land is needed (Meemken & Qaim, 2018).

Many studies have dealt with this topic and have come to some very different conclusions: Maurer (2022) calculates that a complete conversion to organic farming would reduce yields by at least 50 % compared to conventional farming, while overall biodiversity would increase by approx. 108 %. In contrast, a reduction in conventional farming to the same yield would allow 50 % of the current utilized area to be renatured. This would lead to an increase in total biodiversity of approx. 317 %. Seufert et al. (2012) used a comprehensive meta-analysis to examine the relative yield performance of organic and conventional farming systems and found that yield differences depend highly on system and site characteristics. At conditions where the conventional and organic systems are most comparable, they find 34 % lower organic yields. A meta-study analysed 115 studies with more than 1000 observations and found that organic yields are only 19.2 % (±3.7 %) lower than conventional yields and that two agricultural diversification practices, multi-cropping and crop rotations, substantially reduce the yield gap (to 9 ± 4% and 8 ± 5%, respectively) (Ponisio et al., 2015). Another study compared one organic and two conventional farming systems under identical soil conditions. Initially, yields in the organic farming system were lower, but approached those of both conventional systems after 10–13 years, while requiring lower nitrogen inputs, showing lower coefficient of variation, indicating enhanced spatial stability, of pH, nutrient mineralization, nutrient availability, and abundance of soil biota (Schrama et al., 2018). They found that organic farming also resulted in improved soil structure with higher organic matter concentrations and higher soil aggregation, a profound reduction in groundwater nitrate concentrations, and fewer plant-parasitic nematodes. Closure of the yield gap between organic and conventional farming can be a matter of time, they conclude, and organic farming may result in greater spatial stability of soil biotic and abiotic properties and soil processes (Schrama et al., 2018). De Ponti et al. (2012) show that organic yields of individual crops are on average 80 % of conventional yields (standard deviation 21 %). Badgley and Perfecto (2007) state that, contrary to public opinion, the relative yields of organic versus non-organic methods suffice to provide enough calories to support the whole human population eating as it does today. They also conflate data from 77 published studies that suggest that nitrogen-fixing legumes used as green manures can provide enough biologically fixed nitrogen to replace the entire amount of synthetic nitrogen fertilizer currently in use. In their opinion, biological aspects therefore do not stand in the way of a global transition to organic farming. Hepperly et al. (2006) state something similar: during drought years, high soil organic matter under organically managed systems help conserve soil and water resources, thus stabilizing yields of the crops, that even leads to 30 % higher yields in times of extreme weather events. What is possible in sterile study conditions and what corresponds to reality in Germany also differs. Between 2012 and 2020, organically farmed areas across Germany only achieved 47.3 % of the yield of conventional areas. Organic farming achieved 36.5 dt/ha, conventional farming 77.1 dt/ha (Bundesinformationszentrum Landwirtschaft, 2024).

To conclude, organic farming can promote sustainable agriculture and reduce dependence on synthetic, environmentally harmful inputs, improve soil health and fertility, which might even lead to increased crop yields over time. But these changes take time, and time is scarce in a world where demand for food is soaring. A combination of different approaches is necessary to make organic farming justifiable in spite of world hunger. Especially politics can play a critical role in addressing the challenges of organic farming and promoting its development. Suggestions for a multifaceted, linked global strategy to ensure food security have been ongoingly studied (e.g. Godfray et al., 2010).

Can eco-varieties overcome these problems?

One attempt to make ecological farming robust against environmental fluctuations and get stable yields is the use of organic varieties. Since the domestication of cereals began around 10,000 years ago, countless varieties have been bred. The first successes of systematic cultivation can be observed from the 1880s onwards. The ears became heavier and the stalks shorter to prevent lodging. Between 1881 and 1960, yields doubled from approximately 15 dt/ha to over 30 dt/ha (Pentz, 1960). In organic farming, however, these varieties often did not achieve the required protein qualities, and ears close to the ground are exposed to higher disease pressure from soil-borne diseases. This resulted in a loss of local adaptability and resistance, which is why in the 1980s some cereal breeders began to cultivate varieties under certified biodynamic conditions for organic farming. By using the natural soil instead of laboratory conditions and integrating the plants directly into the crop rotation of the farms, the varieties should be adapted optimally to the respective site conditions, resulting in robustness against fluctuations in nutrient availability, plant health, weed suppression, stability and yield. The first winter wheat variety from biodynamic breeding was approved in 2004, and 38 winter wheat varieties have already been registered with the Federal Plant Variety Office by the end of 2023 (see Supplement 1). Two of these varieties are population varieties (Brandex Population and Liocharls Population), also known as ecologically heterogeneous material (ÖHM). Through the usage of more varieties and thus greater genetic diversity in the field, wheat is expected to be better able to adapt to the challenges of climate change and extreme weather events.

In general, varieties of different levels are permitted in organic farming as defined by Euroseends (2019):

- 1st choice varieties: Seed from breeding and propagation under certified conditions. The breeding steps are carried out from the beginning under organically certified conditions, in the case of cross-breeding from the crossing and in the case of selection breeding over a minimum period of 4 years for annual crops and 6 years for perennial crops.
- 2nd choice varieties: conventional seed propagated under certified conditions over at least one generation
- 3rd choice varieties: conventional varieties with untreated seed. The use of this seed is only permitted with authorization.

As there is no mandatory labelling to distinguish between these levels, it is often difficult to differentiate between them. In some cases, conventional breeders advertise organic varieties even though they are only conventional seed. The lack of labelling poses a transparency problem, which also prevents the calculation of acreage and yield of 1st choice varieties, however it is approached in the discussion. In Germany, the control of varieties is the responsibility of the Federal Plant Variety Office (BSA), an independent higher federal authority within the portfolio of the Federal Ministry of Food and Agriculture. Its main tasks include variety protection, authorization and monitoring, as well as the conservation of plant genetic resources (BSA, 2023). Since 2012, the BSA has been conducting an independent "Organic Farming Valuation Test" and integrating organic varieties into its database. These are defined as untreated seeds grown on land that has been farmed organically for many years without the use of chemical treatments or synthetic fertilizers (BSA, 2023). Whether organic varieties, organic farming in general or transformation models that only use partial aspects of organic farming offer a path to greater sustainability is analysed in this thesis.

Aim of this thesis

Humanity needs transformation, but humans revile change. This fundamental contradiction is the reason why change often happens so slowly. Where do we need to start in order to achieve positive shifts that will ensure our long-term survival and that of our environment? Many farmers would be happy to implement more sustainable and environmentally friendly farming practices on their fields but lack good guidance. There are so many factors involved in sustainable farming practices that it is difficult to maintain an overview: Profitability, biodiversity and sustainability are equally important. The CO_2 balance, humus balance, weed infestation, the purchase of technology and operating materials, as well as the well-being of the direct stakeholders (farming families, marketing structures and employees) must all be considered. Nonetheless, the need for biodiversity conservation in agriculture is pressing, as the loss of biodiversity has negative impacts on ecosystem functions, food security, and human well-being.

The aim of my thesis is to evaluate the condition of the arable weed flora in Baden-Württemberg. It also intends to explore the ways in which ecological farming practices can promote biodiversity in crop fields and provide insights into how these practices can be integrated into conventional agricultural systems. I hypothesise that not only organic cultivation promotes biodiversity in the arable landscape, but also that intermediate cultivation methods achieve significantly higher species diversity compared to conventional cultivation including a higher occurrence of rare species. By examining the impacts of ecological farming on accompanying weed diversity, my study will contribute to our understanding of how agroecological approaches can help to conserve biodiversity and support sustainable agriculture. It also provides an outlook on other options for protecting, promoting or restoring biodiversity in the agricultural context, both within Baden-Württemberg and globally.

2 Material and Methods

The study took place in the German Federal State of Baden-Württemberg in the south-west of Germany. Vegetation records were carried out on 374 fields in 2021 and 2022 with farmers who use different cultivation methods specified in the following chapters. The data collected was statistically analysed with regard to species richness in the fields under the influence of various factors. The emergence and distribution of rare species or species of particular value to the environment were investigated. Furthermore, I examined which management and environmental factors have an influence on yields.

2.1 Winter wheat as main study object

As different crops require different nutrients, stand in different densities and reach different heights at different speeds the project therefore specialized in cereals for better comparability. In Germany, winter wheat (*Triticum aestivum* L. em Thell.) is the most grown cereal, accounting for 47.3 % of the total cereal acreage in 2022 (BLE, 2023). It is sown between the end of September and December, with 280 to 520 grains/m². Due to a wide range of thousand grain mass, it is difficult to specify in kg/ha for winter wheat. Most varieties have 2-3 ear-bearing culms per plant, which translates into about 350 - 700 culms/m² (Heyland et al., 1996). Wheat varieties are divided into four quality groups: E-wheat is the so-called elite wheat: those with excellent properties and highest volume yield in baking quality. It is mostly used to mix up weaker varieties or exported. The A-wheats include quality wheat with high protein quality but low volume yield requirements. B-wheats are bread wheats, i.e. all varieties that are well suited for pastry production. Their volume yield may fall short of that of quality wheat. C-wheat is mainly used as animal feed (Brockerhoff, 2015).

Where possible, fields with winter wheat were selected from existing fields, and when lacking winter wheat fields, barley (*Hordeum vulgare* L. subsp. *vulgare*), rye (*Secale cereale* L.), einkorn (*Triticum monococcum* L.), emmer (*Triticum dicoccum* Schrank) and spelt (*Triticum aestivum* subsp. *spelta* L.*)* were also included. Winter wheat was cultivated on 83 % of the mapped fields (Table 1). When wheat is mentioned in the following, this refers to winter wheat.

Table 1: Number of fields per crop

crop	n
barley	39
einkorn	9
emmer	7
rye	13
spelt	14
wheat	**400**

2.2 Participating farmers

The project cooperates with farmers who farm in different ways (Figure 3): 34 organic farms which exclusively use organic varieties (chapter 2.2.1), 24 farms which belong to the Kraichgau Korn market community (chapter 2.2.2), seven farms which farm according to Linzgau Korn guidelines (chapter 2.2.3) and ten farmers who belong to Albkorn (chapter 2.2.4).

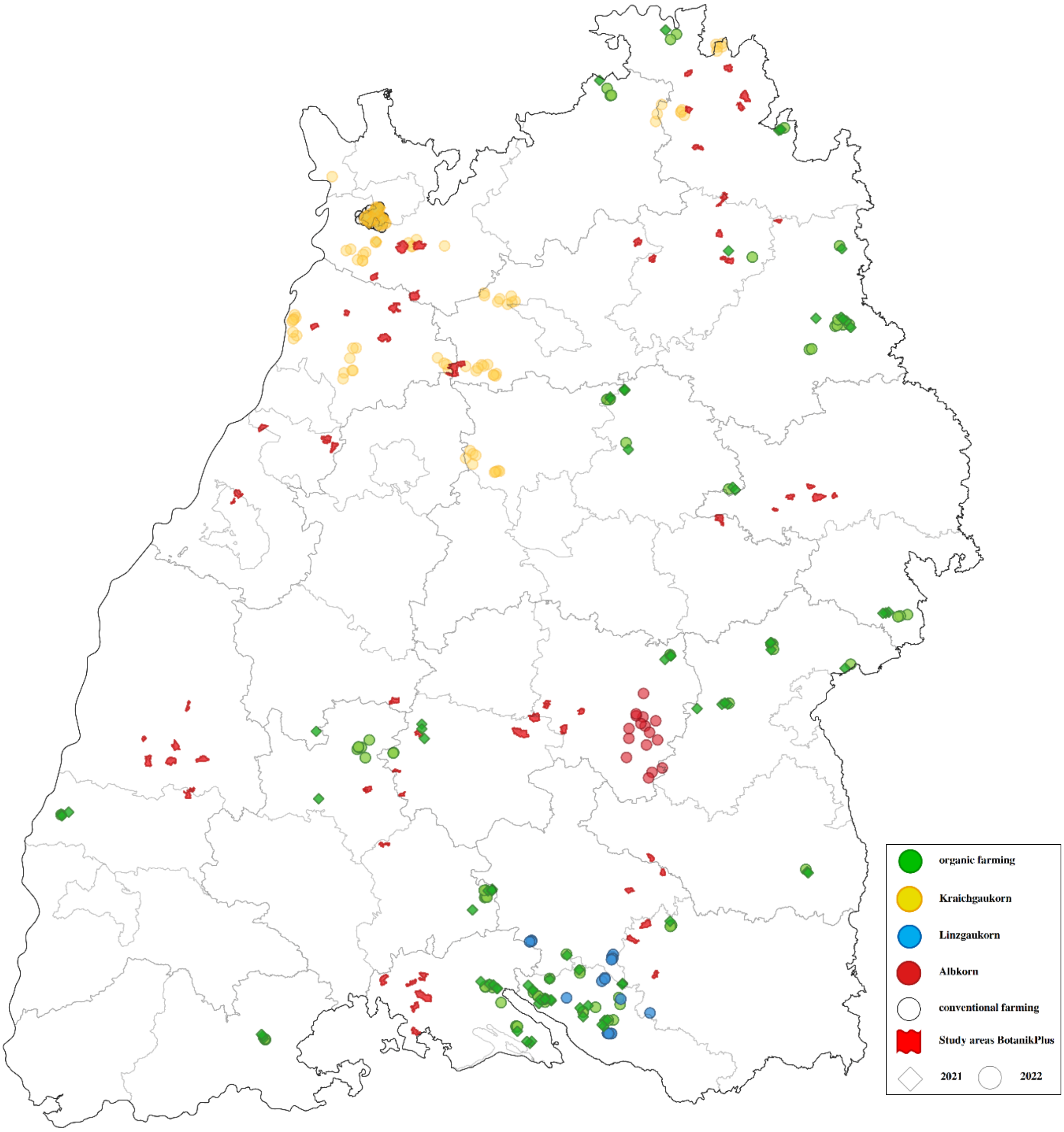

Figure 3: Overview over all mapped fields within the two years of this study, colour indicating the farming method and shape indicating study year

2.2.1 Ecologically certified farmers

The 34 participating farmers with organic certification are each subject to the standards of one of the following three seals: Bioland (n = 13), Demeter (n = 19) and Naturland (n = 2). The farms have converted to organic farming between 1940 and 2019, the legal form being either a legal entity, partnership company, cooperative or sole proprietorship. Their farms are distributed all over Baden-Württemberg to achieve coverage of all relevant bioclimatic regions and soil types prevailing there (Meynen et al., 1962). All 34 farmers are not only certified organic, but also use 1st choice seed propagated under organic conditions. The initial contact and the conduction of the subsequent surveys were largely supported by Cornelia Wiethaler, who also strengthened the bond with the cooperation partners with farm visits. This allowed me to focus on the vegetation surveys.

2.2.2 Marketing community Kraichgau Korn

45 farmers produce grain under the label of the “Marktgemeinschaft Kraichgau Korn w.V.”, in the following abbreviated as KGK, which is characterized by a renunciation of herbicides during the cultivation of crops which are processed via Kraichgau Korn. Therefore, chemicals are not used from the previous year of cultivation on and weed is controlled exclusively by mechanical methods. Based on a typical crop rotation, this system leads to a 33-60 % reduction in the total use of pesticides. The obtained grain is processed by four mills. The products are sold by 75 bakery branches, which exclusively use Kraichgau Korn flour for their products, and 45 additional outlets (see Figure 4). The marketing community was founded in 1990 and places its main focus on regionality and biodiversity. Therefore, the production of Kraichgau Korn grain takes place exclusively in and around the Kraichgau region in Baden-Württemberg. The cereal fields studied are distributed throughout Zabergäu, Leintal, Enzkreis, Kraichgau, Kurpfalz, Hardt and Taubertal, see Figure 4. Kraichgau is a sloped region in northwestern Baden-Württemberg and is bordered by the Odenwald mountains and the river Neckar in the North, the Black Forest in the South, and the Upper Rhine Valley in the West. Heidelberg, Pforzheim and Karlsruhe therefore enclose the Kraichgau region, which comprises approximately 1,630 km^2. It is defined by its fertile Loess deposits that make the region important for agriculture and create a hilly landscape between the Odenwald and the Black Forest, in common parlance called “Tuscany of Germany”. The soils are especially valuable for cereal production, which is the key component of KGK marketing. The marketing community prohibits the use of chemical pesticides, growth regulators or genetically modified micro-

organisms, whereas they are also certified with the QZ ("Baden-Württemberg quality mark") and VLOG (Verband Lebensmittel ohne Gentechnik e.V.). Weeds are regulated exclusively mechanically, mineral or organic fertilizers are applied adapted to the nutritional requirements of the plants, taking the site-specific soil fertility into account. A separate fertilizer requirement calculation is carried out for each field plot. The harvested crop is made storable exclusively by cooling and aeration. All regulations are controlled by unannounced on-site field inspections of every grain field of independent experts, where soil and grain samples are taken. These are analysed and documented by an official laboratory to ensure that they are free of residues, and reserve samples are retained. Flowering strips and short transportation routes additionally contribute to environmental protection (Kraichgau Korn, 2024). 24 of the total 45 farmers in the KGK cooperative participated in our study. Initially, I contacted the two board members Roland Waldi and Volker Kaltschmitt, who invited other members to participate during internal meetings. I asked each farmer to provide up to five fields for wild arable flora mapping. Due to the limited geographical area of the Kraichgau region, and the small total number of KGK members, the potential sample of cereal fields was limited. Nonetheless, the sample size for the KGK cereal fields was relatively large ($n = 139$), and participating KGK farms covered the entire Kraichgau region.

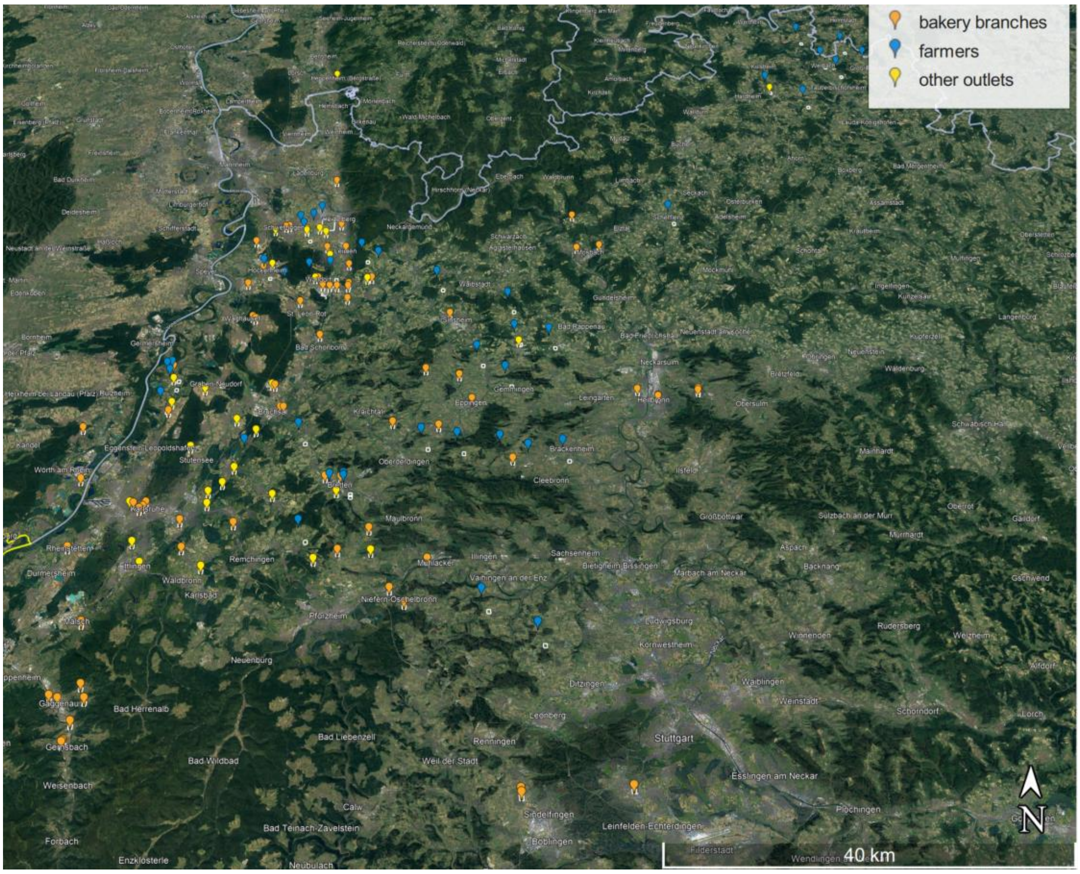

Figure 4: Map of all farmers, bakery branches and other outlets from Kraichgau Korn

2.2.3 Marketing association Linzgau Korn

Linzgau is a hilly landscape in the south of Baden-Württemberg. It borders Lake Constance to the south, the Schussen river to the east, Überlingen to the west and Pfullendorf to the north. Linzgau Korn is a project consisting of 14 farmers from the Linzgau region, one mill and three bakeries (Figure 5). Founded in 2008, they work according to strict guidelines and thus distinguish themselves from conventional grain cultivation and processing. In contrast to Kraichgau Korn and Albkorn, in this association both organic and conventional farmers work together. Wheat, rye, spelt, oats, emmer, sunflower and linseed are cultivated on an area of 160 ha according to the guidelines of the Baden Württemberg quality mark, or, in case of certified organic farms, according to Bioland- or Demeter guidelines. In addition, two more criteria have to be fulfilled: the establishment of flower strips and extensive cultivation of at least 10 % of the area of the managed farm. Various additional measures are also recommended, such as wide-spread sowing, the creation of hedges or deadwood piles or nesting aids for wild bees, birds or bats. In order to ensure that all levels of cultivation, harvesting, transport, storage, milling and baking are carried out in accordance with the contractually agreed regulations, all farms are inspected and controlled by independent inspection bodies (ABCert for Bioland, Certplus for QZ Baden-Württemberg, Demeter inspection association). Farmers can receive advice from experienced Linzgau Korn farmers or specialist advice centres as required (Linzgau Korn, 2024). After I initially contacted the founder of Linzgau Korn, Josef Baader, he established the contact with the seven farmers that took part in the study, four of which have an organic certification.

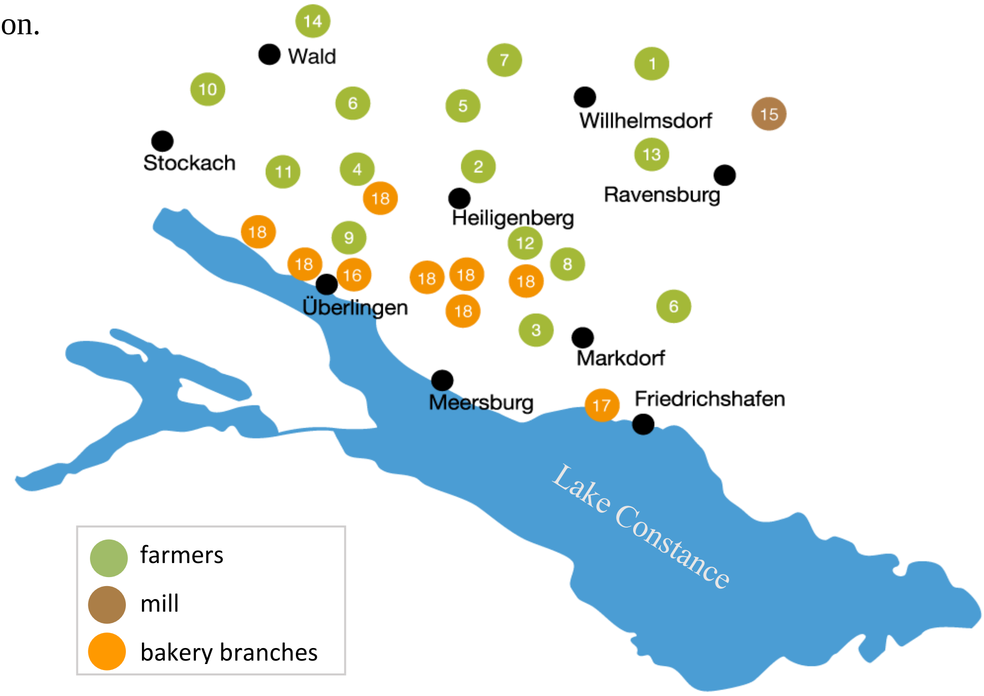

Figure 5: Map of all farmers and bakeries from Linzgau Korn and their mill (Linzgaukorn, 2024)

2.2.4 Marketing community Albkorn

The Albkorn producers' association, founded in 1995, currently comprises 23 farmers, ten bakeries, one mill and one brewery (Figure 6) in and around the Swabian Alb biosphere area (Reutlinger, Münsinger and Ehinger Alb). They promote nature conservation in their fields, especially through flowering strips at the edges of fields and through the preservation of hedgerow biotopes. In addition, special attention is paid to short transport routes: The grain never travels more than 50 km between field, mill and bakery. They only use chemical crop protection when biological or mechanical methods or the resistance capacity of the variety is not sufficient to prevent severe yield losses. Their goal is to perfect a cultivation strategy that requires little or no herbicides and fungicides. The concept of close-to-nature agriculture and environmentally sound production also includes ensuring that all grain varieties used are free of genetic engineering, which is why Albkorn is a member of the campaign "Gentechnikfreie Anbauregion Neckar-Alb" (GMO-free cultivation region Neckar-Alb). The producer rules state, e.g., that the intensity of soil cultivation must be limited to what is necessary, the crop rotation cannot exceed a 40 % share of maize and maize is not cultivated before malting barley. Each member farm must establish a field margin strip of at least one machine width and 30 m in length, as well as min. 100 m² on a field, without applying herbicide on this strip. Humus and nutrient balances must be drawn up, fertilizers may only be applied in accordance with the Fertilizer Ordinance (DÜVO) and must be controlled using the N-min measuring method. Soil testing is mandatory every five years (Albkorn, 2024). I first contacted them by telephone and then presented the project at their annual meeting to generate cooperation partners.

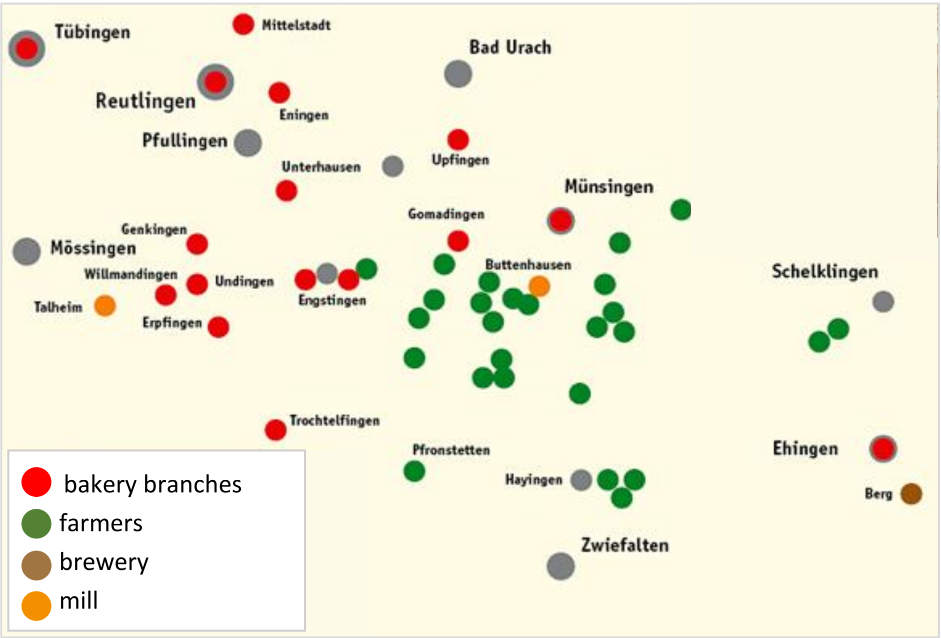

Figure 6: Map of all farmers, bakers, brewery and mill from Albkorn (2023)

2.2.5 Additional data from other studies

In addition to the data collected within the project itself, two further data sets were included. As part of a potential analysis for the re-establishment of field weeds, a joint project of the Bioland Landesverband Baden-Württemberg e.V. and the Institute for Agroecology and Biodiversity e.V. (IFAB), a field weed championship was started in 2016. From this, data from Kraichgau Korn farmers from 2016 (10 farmers, 27 fields), 2017 (7 farmers, 26 fields), 2018 (9 farmers, 29 fields) and 2019 (8 farmers, 27 fields) could be included. In 2016, 21 wheat fields and two fields each with emmer, einkorn and rye were mapped. In 2017, there were 15 wheat fields, four with einkorn, six with rye and one with spelt. In 2018, results from 19 wheat fields, five spelt fields, three with emmer and one each with einkorn and rye were included. In 2019, there were also 19 wheat fields, four rye fields and one each with einkorn, spelt, barley and emmer (Schraml, 2018, 2019). The data set was transformed in such a way that the data are as comparable as possible to my study: their mapping was carried out in the headland and in the middle of the field. The abundance or dominance values were therefore taken from the mapping of the field centre, the species occurring only in the headland were recorded with an *x* (in this study equivalent to “outside the transect”, see chapter 2.3.2). From the mapping at Linzgau Korn, only the average species numbers of the conventionally and organically cultivated farmers are available. In 2016, five fields with winter wheat, four with spelt and three with rye were analysed. In 2018 and 2019, five farms with 13 fields each took part in the studies, two of the farms farmed organically. In 2018, there were seven winter wheat-, one spring wheat-, one barley-, two rye- and two spelt fields. In 2019, there were six fields with winter wheat, one spring wheat-, one oat-, two rye- and three spelt fields.

As part of the “special programme to strengthen biodiversity”, commissioned by the LUBW in 2020 and carried out by the BotanikPlus Institute of Botany and Landscape Sciences (IBL), recent populations of arable flora were determined in order to be able to plan specific large-scale conservation measures (Schach et al., 2023). For this purpose, ten study areas were selected throughout Baden-Württemberg, within which fields were assessed along a selected route from the field path and mapped between 09.05. and 15.09.2021. The resulting species lists of 217 transects was made available to me for comparison with my own data. The data does not relate exclusively to cereal fields, but represents an impression of the entire landscape of the respective areas. The data set of all cereals was used, consisting of 66 wheat-, 16 rye-, 18 oat-, 30 barley-, 21 spelt-, two einkorn fields and one durum wheat field, which results in a total of n = 154 crop fields.

By querying the coordinates, it was possible to find out whether the fields examined had applied for FAKT or MEKA funding in the corresponding year 2021, with MEKA being the predecessor programme of FAKT funding. Although this categorization does not guarantee that the respective field is eco-certified, it does confirm that the associated farmer attaches importance to environmentally friendly crop production and the use of biological/biotechnical measures (MLR, 2017).

2.2.6 Surveys with farmers via LimeSurvey

Surveys were developed in cooperation between biological and political science expertise (Prof. Dr. Jale Tosun, Charlene Marek, Prof. Dr. Marcus Koch, Cornelia Wiethaler and myself). They were conducted with the participating farmers, most of which were distributed and completed via the program LimeSurvey (URZ, University of Heidelberg). All surveys were conducted in German language. Farmers were offered help via telephone if needed by Charlene Marek, Cornelia Wiethaler or myself. This was used to collect all farm and field data, as well as to conduct various political science surveys. The latter were collected as part of a second doctoral thesis, that is also associated with the project, and are therefore not discussed in detail in this one.

The survey on farm structure data asked for the name, address, farm size, altitude, legal form, business sectors, livestock, cultivation guidelines, crop rotations, weed control, cereal varieties used, extreme weather events and disease infestation on the farm, as well as the name, age, gender, education and contact details of a contact person. A second survey asked details on the fields that were mapped during the study: The name, parcel number, coordinates and size of the indicated field, as well as the soil types occurring there had to be stated. In addition, it was asked which previous crop had been cultivated on this field, how, at what depth and with what frequency the soil had been worked, which fertilizer had been applied, when and in what quantity which cereal variety had been cultivated and from where it was obtained, when it had been sown, with which drill row spacing and with which seed thickness. In a last survey, additional information on weed control and fertilization was asked for each field. Farmers were also asked when the fields had been harvested, when (if) the stubble had been turned and what yield in dt/ha they had on each field. If allowed for the respective cultivation method, it was also asked whether and which plant protection products were applied and in what quantity. As the survey was often not completed in full by the farmers, a follow-up telephone survey was conducted in an attempt to fill in the gaps as far as possible.

2.3 Mapping of the fields

The mappings within the scope of this study took place in 2021 and 2022. In 2021, 25 wheat fields, three spelt fields, one einkorn- and one emmer field cultivated under Kraichgau Korn standards were mapped. In addition, there were 17 conventionally cultivated barley fields from the same farmers. Furthermore, there were 84 winter wheat fields from organic farmers. In 2022, these organic farmers submitted 79 wheat fields and one with barley for mapping, and Kraichgau Korn added another 92 wheat fields, three spelt fields and one rye field. The 15 wheat fields, 17 barley fields and one spelt field from conventional cultivation were mapped by random sampling in the Kraichgau region without any background knowledge about the field or its owner. In addition, two more market associations were mapped: Albkorn with 15 wheat fields and one barley field and Linzgau Korn with 17 wheat fields and one barley field.

As the number of fields and the distance between the individual fields was too high to map them alone, I had support from various people: Markus Sonnberger was employed for mapping over a period of two years. In response to an inquiry in the monthly journal of the Botanical Association of Southwest Germany (BAS), 15 volunteers with botanical knowledge (Christian Andres, Gabriele Baier, Petra Bauer-Kutz, Dorothee Braband, Ulrich Buck, Jutta Hofmann, Claudia Huesmann, Anja Lehmann, Hanna Mertens, Gunter Müller, Heinz Reinöhl, Lennard Thale-Bombien, Karin und Martin Weiß, Steffen Wolf) joined the team and under the supervision of myself and Dr. Peter Sack, 11 students mapped some fields as part of their final theses or internships (Anna Freudenberg, Anna Lisa Galle, Celine Geiger, Eva Holzberg, Charlotte Lauel, Lukas Meysen, Frithjof Pölzing, Linus Raphael Pörsel, Jan Schäfer, Robin Schaugg, Ron Eric Stein).

So as not to overlook early bloomers either, mapping was carried out in all years between 17.05. and 29.06., with an exception of three fields that were mapped 09.07.2022 after one of the volunteers was unable to perform at short notice.

2.3.1 Determination of transects

At least one transect per field was defined. According to Hofmeister and Garve (1998), the minimum size of a transect in arable weed communities is 25 m^2, whereby in species- and individual-poor stands the transect is to be extended to the size of 100 m^2. The size of the transects in the data collected in this work was therefore set at 90 m^2, 3 m wide and 30 m long, aligned parallel to the lanes and at least two metres from the field edge and five metres from the headland to minimize edge effects. This is because marginal areas and headlands are mostly exposed to a lower number of herbicides, receive more light and the immigration of species from adjacent sites is simplified. Therefore, these areas are not suitable as a representative section of the entire field (Hofmeister & Garve, 1998).

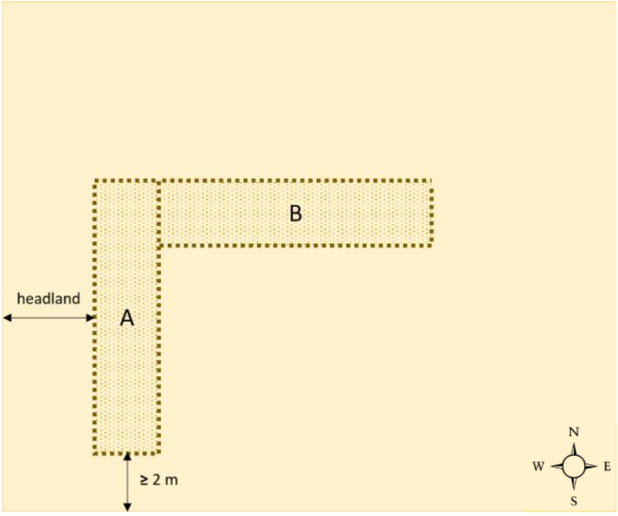

Figure 7: Transects as mapped on the fields (transect A = standard)

A sample of 41 fields was used to investigate how the number of species found changes depending on whether the transect studied runs parallel to the edge of the field two metres away from it (see transect "A" in Figure 7) or from the same starting point towards the centre of the field (see transect "B" in Figure 7). In these 41 fields, two transects were recorded and compared with each other, as shown in Figure 40. Only ecological fields from the same year (2021) were used to avoid further influence from external circumstances. All further recordings were made according to the scheme of transect A. In order not to destroy too much in the field, mapping in the actual centre of the fields was omitted. The fields where both a longitudinal and a transverse transect were mapped were treated as follows in the overall evaluations: the longitudinally mapped transect was used including the scale mapped according to Braun-Blanquet, all additional species found in the transversely mapped transect were recorded with an x, which indicates that the species was found outside the mapped transect, but does not provide any information on the abundance of this species.

2.3.2 Methodology for vegetation records

The most widely used vegetation recording method, which therefore also provides the most scientifically comparable results, was introduced by Braun-Blanquet (2013). In this combined scale, both abundance and dominance of species are recorded, ranging from r to 5. In the transect, all species present were determined and their abundance counted (if the number of individuals was low) or estimated (if the number of individuals was higher). If a species was found outside the previously determined transect, it was marked with an x (table 2).

Table 2: Braun-Blanquet scale for vegetation records and conversion to percentage value

symbol	number of individuals	cover	Percentage value *(Güngör, 2011)*
r	rare, one specimen	well below 1 %	0.01
+	2 to 5 individuals	up to 1 %	0.02
1	6 to 50 individuals	up to 5 %	0.04
2	more than 50 individuals	5 to 25 %	0.15
3		26 to 50 %	0.375
4		51 to 75 %	0.625
5		76 to 100 %	0.875
x	sightings outside the transect		0.01

In order to guarantee a uniform procedure, a standardized sheet was drawn up at the beginning, which was filled in individually for each field (see digital appendix). In addition to general data (name of the mapper, date, coordinates of the transect), site- and use-specific data (row spacing, height of the crop, characterization of the surroundings) were recorded. After arrival at the field, photos were taken of the surroundings, the field and the mapped transect. The height of the crop was measured with a folding rule and the number of ear-bearing stalks per running metre was determined.

The estimate of the species richness was given using the Braun-Blanquet scale and the occurrence of the segetal flora was documented on a scale from extensive to fragmentary. To ensure that all plants were correctly identified, all volunteer mappers and students were encouraged to herbarize each new species found, and to photograph any plants they were not entirely sure of identifying. These were re-identified in the laboratory with the aid of binoculars and literature and species identification was corrected if necessary. All herbarized specimens can be found in the Herbarium of the University of Heidelberg (HEID), tagged with a specific code to ensure the assignment to the according field, mapper and background data (see digital appendix). Individuals that can be categorized as trees, such as *Juglans regia* or *Quercus robur*, were not recorded as field flora. They can be explained by the seed input of trees at the respective field edge, but do not belong to the expected species spectrum of the arable flora.

2.4 Evaluation of the mapping results

The vegetation data collected was analysed statistically and presented graphically and on maps. All factors influencing the number of species and thus also the calculated Shannon Index and yield were analysed in an overall analysis. In addition, the influences of the analysed factors on the Shannon Index and yield were examined individually, which was illustrated with box plots or jitter plots.

2.4.1 Used programs and statistical analyses

Overview maps showing the distribution of the analysed fields and field-specific values calculated from the vegetation surveys were displayed using QGIS (version 3.16.1) (QGIS Development Team, 2022).

To assess the assumption of normal distribution for the data, several tests were conducted. The results of these tests are presented in the digital appendix. To visually assess the normality of the data distribution, quantile-quantile (QQ) plots were generated for the variables of interest (number of species and Shannon Index). In cases where the data did not exhibit normal distribution based on the QQ plot analysis, I explored alternative probability distributions. The negative binomial distribution was fitted to account for overdispersion, while the Poisson distribution was fitted as an alternative to the normal distribution. Central tendency and dispersion were computed for the variables ‘number of species’ and ‘Shannon Index’ and distribution plots were generated to visualize the fitted distributions.

For the boxplots, statistical comparisons between groups were performed using the two-sample t-test. It was chosen for its effectiveness in comparing means between two independent groups when the data is approximately normally distributed and the variances are approximately equal. The t-test was applied to assess whether there were statistically significant differences in the mean values of the studied factors between the different farming methods and other groups.

To investigate the relationship between different factors in the jitter plots, a linear regression analysis was conducted. The linear regression model aimed to assess how changes in one factor influence outcomes related to another factor, estimating the coefficients of the regression equation, including the intercept and slope to quantify the relationship between two factors. To assess its statistical significance, p-values and adjusted R^2-values were analysed. Additionally, diagnostic checks were performed to evaluate the assumptions of linear regression, including linearity, independence of observations, homoscedasticity, and normality of residuals. These checks ensured the validity of the regression analysis and the reliability of the obtained results.

All statistical analyses were conducted using R version 2023.12.0 (R Foundation for Statistical Computing, Vienna, Austria), and a significance level of $\alpha = 0.05$ was used for all tests.

Correlation analysis was performed to assess the relationships between variables in the data set using Pearson correlation coefficients. I visualized the results in a correlation matrix to identify patterns of association among variables. Principal Component Analysis (PCA) was employed in this study to explore the underlying patterns of biodiversity data and to identify key factors driving variation among the sampled fields. PCA is a widely used multivariate statistical technique that enables the reduction of complex data sets into a smaller set of orthogonal variables, known as principal components, while retaining as much of the original variability as possible. The decision to use PCA was based on its ability to explore the relationships and structure within the biodiversity data, which included a wide range of environmental variables. By reducing the dimensionality of the data set, PCA facilitates the visualization and interpretation of complex patterns. Furthermore, PCA can prioritize variables based on their contribution to overall variability, thereby helping in the identification of key drivers shaping plant biodiversity patterns across different habitats or regions. Since I analysed not only numeric data but also qualitative data, PCA offers the most robust approach to extract information.

R packages used:

- ape (Paradis et al., 2019)
- dplyr (Wickham, François, et al., 2019)
- factoshiny (Vaissie et al., 2020)
- ggplot2 (Wickham, 2011)
- ggpmisc (Aphalo, 2016)
- ggpubr (Kassambara, 2020a)
- ggsignif (Ahlmann-Eltze et al., 2017)
- gridExtra (Auguie et al., 2017)
- magrittr (Bache et al., 2022)
- patchwork (Pedersen, 2019)
- readxl (Wickham, Bryan, et al., 2019)
- rstatix (Kassambara, 2020b)
- tidyr (Wickham & Wickham, 2017)
- vegan (Dixon, 2003)

2.4.2 Shannon Index and Evenness

Biodiversity can be categorized into different types at species level. To determine the species diversity or α-diversity of an area, species richness is often used, which according to Whittaker (1972) can be measured as the number of species in relation to a standardized sample size, in this case as the total number of species identified per examined field. The γ-diversity refers to the species richness within a large area in which the α-diversities are summarized and β-diversity indicates how many different species exist between different systems. However, as biodiversity depends not only on the number of different species, but also on the number of individuals, there are diversity indices. These mathematically weight species according to their frequency distribution, i.e. their abundance (number of individuals) and dominance (cover). The most commonly used indices are Simpson's Index and Shannon Index. Simpson’s index (Simpson, 1949) is particularly sensitive to changes in the relative abundances of the most important species, whereas Shannon's index (Shannon, 1948) is particularly sensitive to the number of rare species in a community (James & Rathbun, 1981), hence for this evaluation the Shannon Index is better suitable was calculated for further analysis of the collected data.

$$H' = -\sum_{i=1}^{s} p_i \cdot ln\, p_i \qquad \text{with} \qquad p_i = \frac{n_i}{N}$$

where:

H' = Shannon-Wiener diversity index
s = total number of species
n_i = percentage value of species
N = sum of the percentage values of all species
p_i = relative proportion of species i between 0 and 1 → division of the percentage value of a species by the total value

For the calculation, the frequency classes according to Güngör (2011) were converted into percentage values (see chapter 2.3.2). In the Shannon Index, each species contributes to the overall result. The lower the number of species, the more susceptible the index is to outliers, as these then have a major influence. Therefore, if there is a high number of species with an uneven distribution of individuals, the Shannon Index can be similar to a low number of species with a very even distribution of individuals. Evenness (Pielou, 1966) was therefore also calculated to serve as an evaluation approach for diversity indices, as these only allow limited statements on a comparison of different areas due to site and use influences (Kühn & Pfadenhauer, 1995).

$$E = \frac{H'}{\ln(s)}$$

2.4.3 Weather data and soil values

Weather and soil data on the coordinates of the individual fields were retrieved from the Internet. The weather data originates from the German Weather Service (DWD) (Deutscher Wetterdienst, 2024) and was interpolated between the individual weather stations so that the retrieved values apply directly to the requested coordinates. The following information was read:

- Maximum, mean and minimum air temperature in °C, monthly resolution
- Precipitation in mm (1 mm = 1 l/m^2), monthly resolution
- Drought index (according to De Martonne ($dMI = \frac{P}{T+10}$)), monthly resolution

An annual average was calculated from the monthly average values of the year in which the mapping was carried out. For some analyses, only certain months were included. To determine whether there was frost, I examined whether the minimum monthly average temperature fell below 0 °C in at least one month.

The soil data was read from the map viewer of the Baden-Württemberg State Office for Geology, Raw Materials and Mining (LGRB-Kartenviewer, 2021). The data originates from the measuring point closest to the queried coordinates, which is why the information drawn from it cannot make a direct statement about the analysed field, but rather about the surrounding landscape area. The retrieved information includes:

- Humus quantity 0-1 m in t/ha: average humus quantities of soils up to 1 m below ground level in a 500 m grid
- C_{org} quantity 0-1 m in t/ha: average C_{org} quantities of soils up to 1 m below ground level in a 500 m grid
- N_field: Calculated nitrogen surplus on arable land in order not to exceed a specified average nitrate concentration of 50 mg/l in the total seepage water of a municipality (LGRB-BW BÜK200: Nitratauswaschung, last update 31.12.2004)
- Seepage water in mm/a (Sickerwasser, data from 1961-1990) and Soilwater exchange rate (Bodenwasseraustauschrate) in %: basis for calculation of the nitrogen surplus

2.4.4 Red list and (especially) valuable species

The Red List of ferns and flowering plants of Baden-Württemberg (Breunig & Demuth, 2023) offers an actualized classification of the degree of endangerment for all species and subspecies that are considered an integral part of the flora of Baden-Württemberg. Additionally, it provides a categorization of the nature conservation significance of the individual taxa. In combination with the endangerment situation, the importance of a taxon as an indicator for near-natural biotopes and sites and its significance for the character of nature and landscape is considered (Breunig & Demuth, 2023). Both the Red List status and the nature conservation significance value (NB = Naturschutzfachliche Bedeutung) are considered in the evaluations.

Furthermore, the evaluations refer to valuable and especially valuable species. This categorization originates from a preliminary study conducted by the Institute of Botany and Landscape Sciences IBL Karlsruhe for the study "Determining the potential for promoting the flora accompanying arable land in Baden-Württemberg", which was carried out to determine recent populations of the flora accompanying arable land. This involved interviewing people from nature conservation and landscape management organizations drawing up a list of arable wild herbs that are of particular importance in Baden-Württemberg from a nature conservation perspective (Schach et al., 2023). The 112 species named are divided into valuable (n = 39, “w”) and especially valuable (n = 79, “bw”) species, whereby the former are characteristic of fields with a species-rich wild herb flora and are important for the protection of biodiversity typical of the natural environment. Particularly valuable plants are confined to fields with special site conditions, such as calcareous soil or acidic, poor sites with a long history of suitable farming. Many of these species are also on the Red List, with the exception of ubiquists, problem weeds and recent neophytes. When referring to both valuable and especially valuable species, the term (especially) valuable species is used below. A third categorization was made by classifying (especially) valuable species as R species (“R”) if they are particularly suitable for the re-establishment of arable associated plants, as they are closely linked to agricultural use or indicate special site conditions. In order to be able to compare the results of this study as well as possible, the same system was used for the species found in this study and categorized into four value categories (Schach et al., 2023):

category 0 = without or with only very sparse, species-poor wild herb flora
category 1 = with arable weed flora without valuable species, but species-rich
category 2 = with arable weed flora, including valuable species
category 3 = with arable weed flora, including particularly valuable species

The arable weed flora of a field was assessed as species-rich (category 1) if at least five species from the following list were detected:

Aethusa cynapium, Alopecurus myosuroides, Anagallis arvensis, Arenaria leptoclados, Arenaria serpyllifolia, Centaurea cyanus, Chaenorhinum minus, Erodium cicutarium, Erucastrum gallicum, Erysimum cheiranthoides, Euphorbia helioscopia, Fumaria officinalis, Fumaria vaillantii, Geranium columbinum, Geranium dissectum, Geranium rotundifolium, Lamium amplexicaule, Lamium purpureum, Matricaria recutita, Mercurialis annua, Myosotis arvensis, Papaver lecoqii, Papaver rhoeas, Sinapis arvensis, Sonchus arvensis, Spergula arvensis, Thlaspi arvense, Valerianella carinata, Valerianella locusta, Vicia tetrasperma, Vicia villosa, Viola arvensis.

2.4.5 Plant communities and Ellenberg indicator values

Plant communities are a characteristic composition of species, whose formation depends on the prevailing site condition. Due to their similar combinations of species in similar biotopes, they can be classified in the phytosociological systematics (Braun-Blanquet, 1964). Where possible, the vegetation plots were assigned to a plant community.

Heinz Ellenberg (1974) investigated the correlations between the ecological requirements of species and their locations and established the concept of indicator values. With ordinal numbers from 1 to 9, location factors of a plant growing in Central Europe are characterized: L (light), T (temperature) and K (continentality) hereby correspond to climatic factors, F (moisture), R (pH-value), N (nutrition) and S (salt) to edaphic factors. The indicator values can therefore be used to deduce the conditions under which a plant has the greatest competitive strength. The probability for plants to be found in locations that correspond exactly to the indicator values is greater than for locations that deviate from them. The average Ellenberg indicative values were calculated for each vegetation survey. In addition, the general distribution of the values of the plants found was analysed.

2.5 Plant biodiversity in Baden-Württemberg

Bioclimatic conditions, landscape effects and soil type are only few of many factors on which the arable wild flora depend, both in richness and composition (Tscharntke et al., 2021; Tscharntke et al., 2012b). To explore the overall vascular plant biodiversity of Baden-Württemberg, we determined the baseline diversity of arable weeds in Baden-Württemberg by analysing the floristic database of the Natural History Museum in Stuttgart. This was done to monitor the potential effect of regional agriculture on our study design and to compare the mapped species diversity with respective regional total vascular plant biodiversity in Baden-Württemberg to establish a general indicator for the actual vulnerability of wild arable flora on a regional scale. Besides the updated Red List of fern and flowering plants Baden-Württemberg (Breunig & Demuth, 2023) no systematic monitoring of arable wild flora was executed since Pierny (1994). The floristic database of the State of Baden-Württemberg is continuously updated and includes over 3 million records from the past century. It is freely accessible at http://www.flora.naturkundemuseum-bw.de/. Floristic data can be examined and exported at http://www.florabw.recorder-d.de/. As the geographic accuracy of documented occurrence data varies, we aggregated the resolution on a scale of ¼ of the ordnance survey map (MTB 1:25,000, 10 × 10 km), which is equivalent to an area of 25 km^2. We limited the final data set after database screening to occurrence data from the past 20 years, generating 475,814 data points. In the final data set, we replaced all ¼ MTB with total species numbers smaller than a cut-off value of 100 (considering the total data set of ¼ MTBs) by the arithmetic mean of its eight direct neighbours to minimize the impact of erroneous reports or potential lack of mapping data, as we already did in Koch et al. (2023).

From this, we generated a data set of the total vascular plant diversity (A) of Baden-Württemberg and the AgroBioDiv species richness (B), taking only the species found on the studied fields into account. The total vascular plant diversity (A), the AgroBioDiv species richness (B) and the overlap of both (C = B/A) were imported into QGIS (QGIS Development Team 2021, open source: http://qgis.osgeo.org). IDW (inverse distance weighting) algorithm (Bartier & Keller, 1996) was applied by Dr. Markus Kiefer as implemented in QGIS (version 3.16.1), and species richness scores and coordinates of the original ¼ MTB were used to

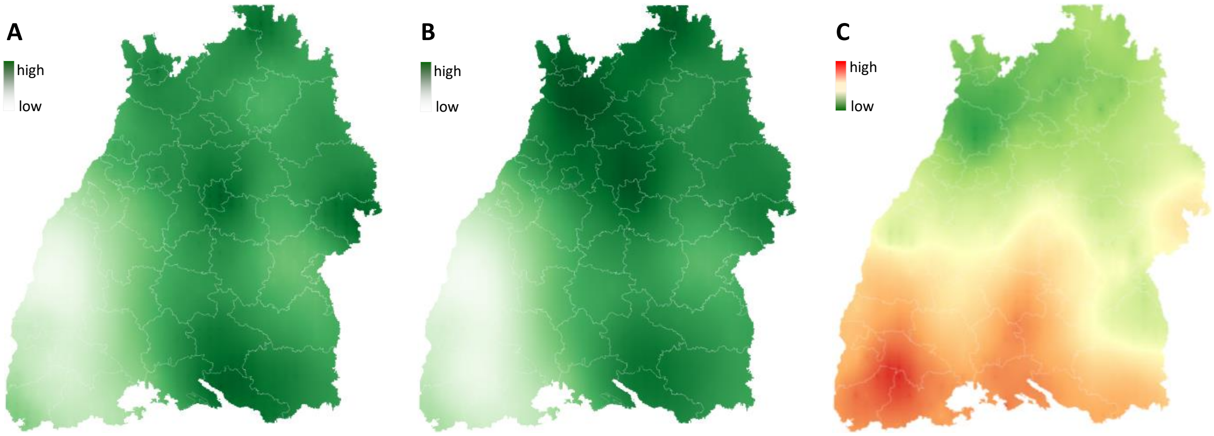

Figure 8: A: Total number of species in Baden-Württemberg according to Flora BW (corrected for significantly low MTB). B: Current agrobiodiversity (wild arable species from AgroBioDiv biodiversity monitoring) according to Flora BW. C: Potential vulnerability of wild plant species from arable fields on landscape scale (resolution of 25 km^2). Landscape-level diversity measures are not different, hence, allowing direct comparisons of monitoring results on local fields.

calculate respective raster layers. A colour code was adjusted to highlight respective differences in species richness (Figure 8). A map-based visualization of data set C measures the putative vulnerability of wild arable flora by showing the fraction of documented wild arable flora to the total potential vascular plant biodiversity in Baden-Württemberg. Lower percentages represent a higher vulnerability and thus an increased risk of species' decline.

Additionally, we used this data to generate a list of 80 representative wild plants (see electronic Appendix "80_species_list"), that are characteristic species of the agricultural landscape according to Pierny (1994). Very locally distributed species and taxonomically not well-defined taxa were excluded. From this list of 80 species, 42 (52,5 %) occur in our vegetation recordings, 15 of them (> 35 %) with a frequency larger than 10 %, therefore covering a representative fraction of the weed diversity in Baden-Württemberg. Here, we used the species richness of the 80 species (Figure 9 D) to calculate another overlap (Figure 9 E = D/A).

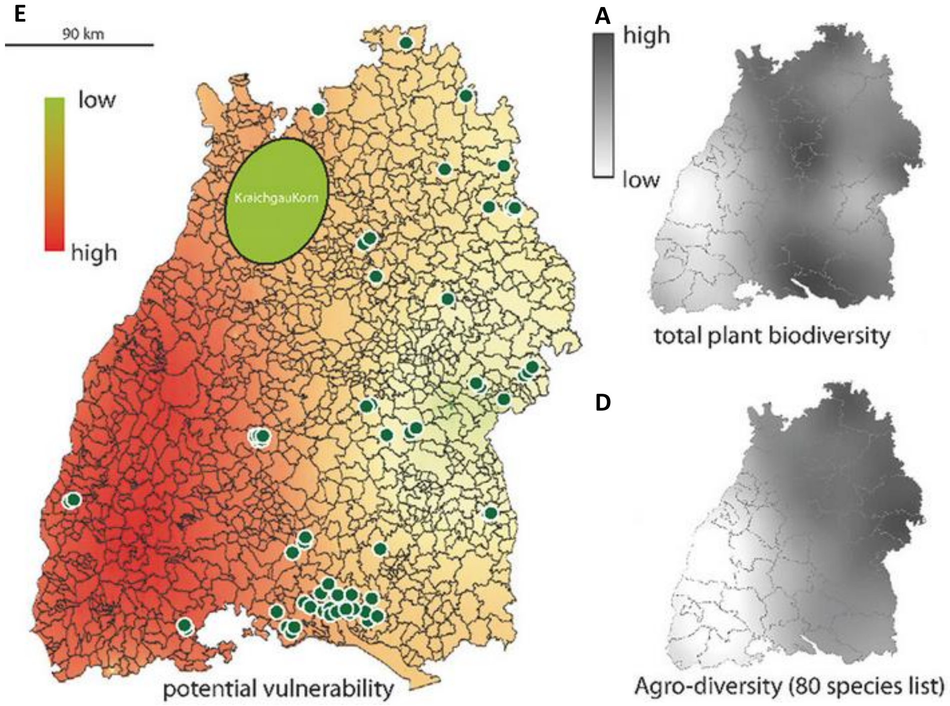

Figure 9: Potential vulnerability of arable plants (E = D/A) when considering only the 80 species list (D), location of the Kraichgau region (light green) and ecological farm sites (dark green) (Koch et al., 2023)

Furthermore, we studied the regional variability of the fields at the landscape-level (¼ MTB, 25 km^2 resolution) by comparing the total potential number of vascular plant species following the floristic database of Baden-Württemberg with our total number of recorded arable flora species for all ¼ MTBs of all farm sites. Seeing no difference between regions with different cultivation methods (tested for ecological farming and Kraichgau Korn) allows direct comparison with our collected field data.

3 Results

3.1 Species diversity

286 different species were found in total within the scope of this investigation. In 2021, 235 species were found and 190 in 2022. Shoots from trees were not counted. A comparison of all studied cultivation methods (Figure 10) tests the hypothesis that the most species rich fields are organically cultivated, but intermediate agriculture also achieves higher species diversity than conventional farming.

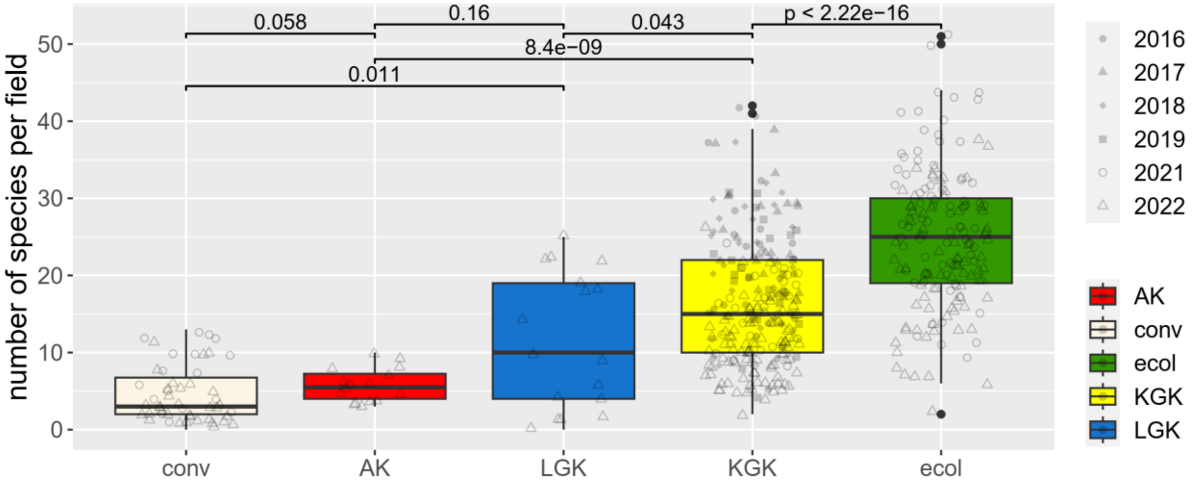

Figure 10: Ecological farming achieves the highest number of species per field, followed by the three intermediate cultivation methods. Conventionally farmed fields are the least biodiverse. Shape indicating sample year (n_{conv} = 50, n_{AK} = 16, n_{LGK} = 17, n_{KGK} = 232, n_{ecol} = 163)

The number of species found on each crop field was highest in ecological farming. In total, 230 different species were found all over the ecologically farmed fields with an average of 24.39 species per field (27.77 in 2021 and 20.88 in 2022), the most species-rich field had 51 weed species, on one field no weed was found at all. In total, 230 different species were found on ecological fields, 209 in 2021 and 151 in 2022. In Kraichgau Korn, the species average was 16.31 over all studied years. In total, 209 different species were found on all Kraichgau Korn-fields (89 in 2016, 104 in 2017, 101 in 2018, 89 in 2019, 103 in 2021 and 125 in 2022). The most species per field, 42, were found on a wheat field in 2016. Within the year 2022 that can be compared to the other marketing associations the mapped maximum was 26 species, on two fields only two species each were found. In 2016, the species average was 20.30, in 2017 it was 25.08, in 2018 it was 22.00, in 2019 it was 19.26, in 2021 it was 15.63 and in 2022 it was 10.48 species per field. In Linzgau Korn there was also one field without field flora, the most species-rich field was a wheat field with 25 different accompanying plant species. The average was 11 species per field, the total number of different species was 64. The fields of Albkorn had an average of 5.75 species, a maximum of 10 and a minimum of 3 species per field. In total, 33 different species were found. The conventionally cultivated fields inhabited in total 49 different species, 33 were found in 2021 and 34 in 2022. The fields had the lowest average value with 4.68 species (7.18 in 2021, 3.42 in 2022). Here, too, there was one field with no associated flora at all, and the maximum value was reached by a barley field with 13 species. The wheat field with the most species found contained 11 species.

The correlation coefficient between number of species and Shannon Index is 0.8131658, indicating a strong positive correlation between the two variables. Looking at the Shannon Index of each field, I split the data in three groups at first (Figure 11): the fields that used chemical weed control (cwc), the ones that use no chemical weed control in the respective year, but lack organic certification (w/o), and the ones that do have an organic certification (ecol). The mean Shannon Indices of all three categories differ significantly from each other, ecologically farmed fields show the highest values and chemically treated fields show the lowest values.

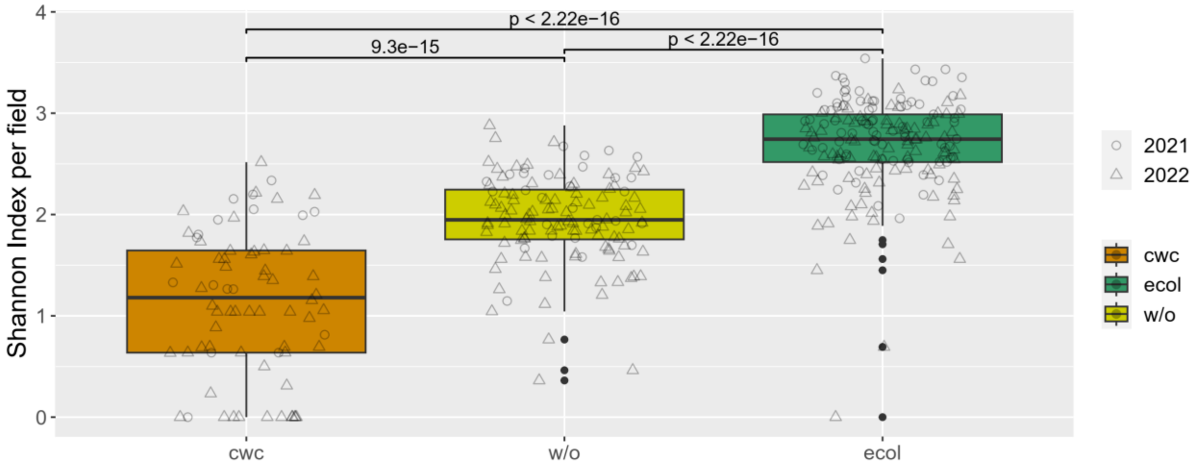

Figure 11: Organically farmed fields (ecol) show a higher Shannon Index than conventional fields without chemical weed control in the respective year (w/o). Fields with chemical weed control (cwc) have the lowest Shannon Index (n_{cwc} = 74, $n_{w/o}$ = 232, n_{ecol} = 172), shape indicating sample year

Of the fields that use chemical weed control, some belong to the Albkorn market community, which nevertheless try to have a positive impact on the environment with measures such as flower strips. Despite these efforts, Albkorn does not differ significantly from either conventional farming or Linzgau Korn. The latter include fields where chemical weed control was used, but also fields from organic farming. The difference between conventional farming and Linzgau Korn is significant, as is the difference between Kraichgau Korn and Albkorn. The Shannon Index in organic farming is significantly higher than that of all other farming methods, even if the organically farmed Linzgau Korn fields are excluded (Figure 12).

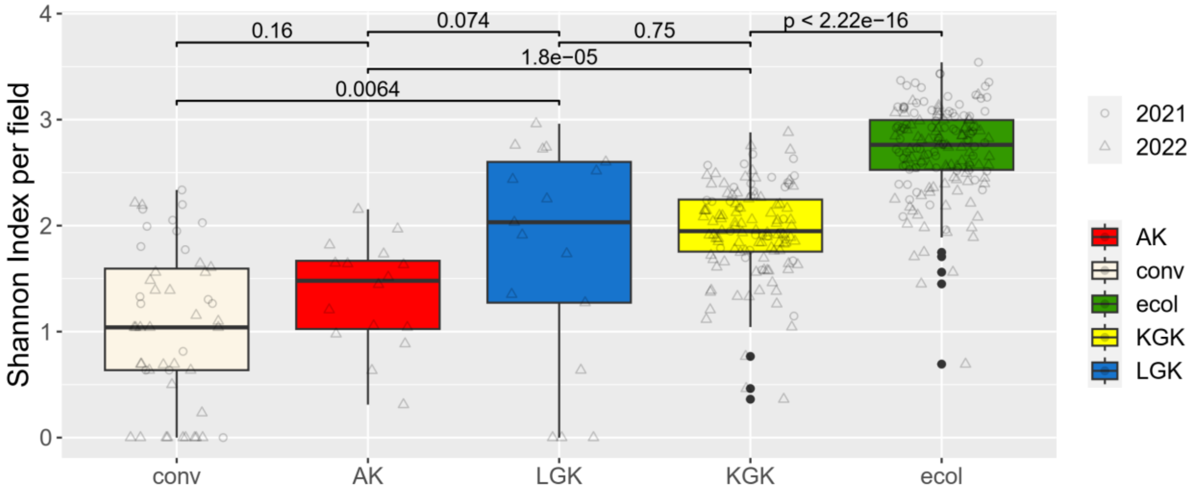

Figure 12: Ecological farming achieves the highest Shannon Index, followed by the three intermediate cultivation methods. Conventionally farmed fields have the lowest Shannon Index. Shape indicating sample year, only 2021 and 2022 (n_{conv} = 50, n_{AK} = 16, n_{LGK} = 17, n_{KGK} = 123, n_{ecol} = 163)

When including the data set from 2016-2019 (Figure 13), the average Shannon Index rises to a value above that of Linzgau Korn. However, the statistical significance of the differences between the individual growing communities does not change.

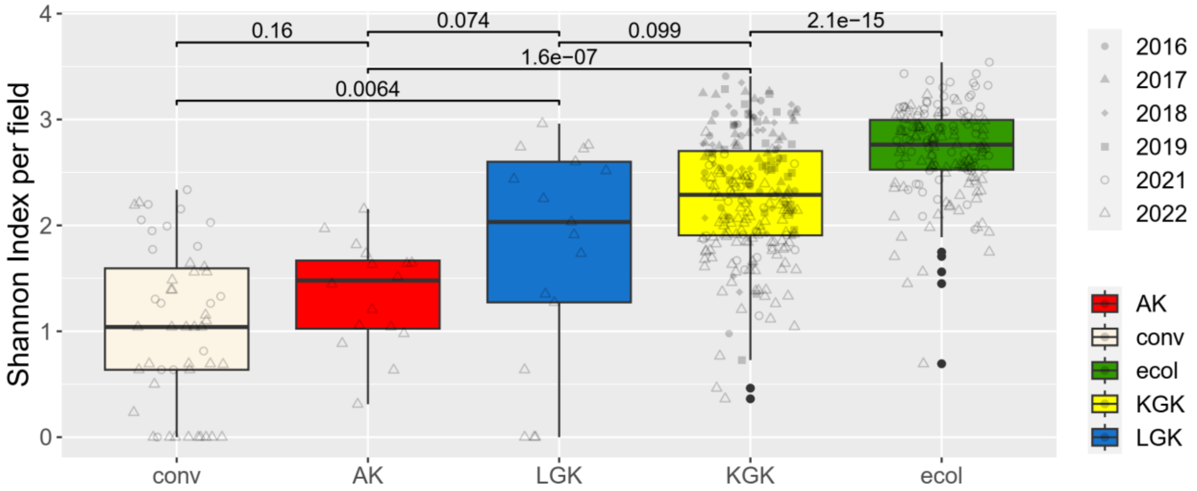

Figure 13: Shannon Index per cultivation method, shape indicating sample year, including KGK data from 2016-2019 from the field weed championship (n_{conv} = 50, n_{AK} = 16, n_{LGK} = 17, n_{KGK} = 232, n_{ecol} = 163)

When plotting Evenness against Shannon Index (Figure 14), it becomes clear that the ecological fields have the highest and overall consistent Evenness with an equally high Shannon Index. Linzgau Korn shows strongly varying values of the Shannon Index, but a consistently high Evenness. Kraichgau Korn performs slightly worse due to a few outliers. The conventional and Albkorn fields have the lowest values both in terms of Evenness and Shannon Index.

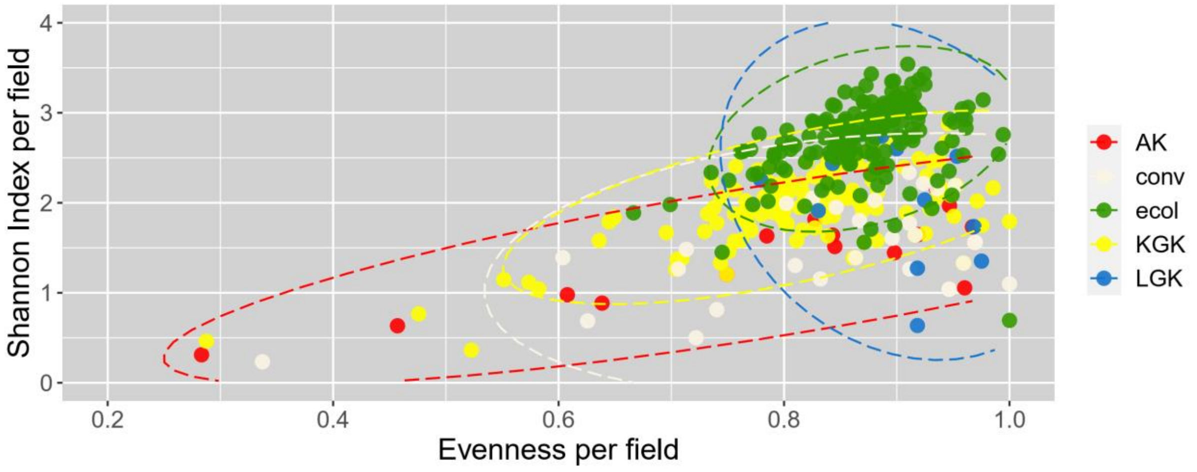

Figure 14: Comparison of Shannon Index and Evenness per field, colour indicating cultivation method, (sample years 2021 + 2022, n_{conv} = 50, n_{AK} = 16, n_{LGK} = 17, n_{KGK} = 123, n_{ecol} = 163)

3.1.1 Analyses based on the data set of the ecological fields

The data set of organic fields was of similar size in both years and had a relatively large sample size with n = 83 in 2021 and n = 81 in 2022. The participating farmers varied only very slightly, which is why both the location and farming methods of the fields remained comparable on average. The investigated organic fields were cultivated according to three different cultivation guidelines that qualify for a certification of organic farming: Bioland, Naturland and Demeter. All three showed very similar results in terms of the Shannon Indices of the studied fields, no significant difference is detectible (Figure 15).

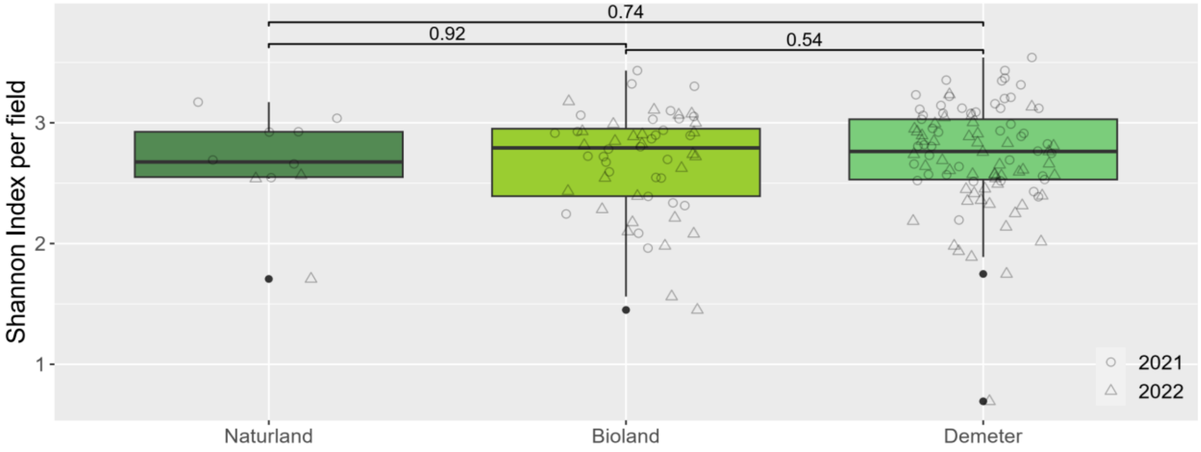

Figure 15: Shannon Index does not differ between the organic farming certifications ($n_{Naturland}$ = 10, $n_{Bioland}$ = 56, $n_{Demeter}$ = 197), shape indicating sample year

This data set is therefore well suited for comparing the two years of mapping 2021 and 2022 and determining whether there is a significant difference in species richness despite the comparability of the data sets. The number of species found, as well as Shannon Index H' and maximum species richness H_{max} differ significantly from each other. The Evenness E shows no significant differences between the two years (Figure 16). The median Shannon Index is 2.8975 in 2021 and 2.6086 in 2022, which makes a difference of 0.2889. The mean Shannon Index is 2.8596 in 2021 and 2.5541 in 2022, which makes a difference of 0.2058.

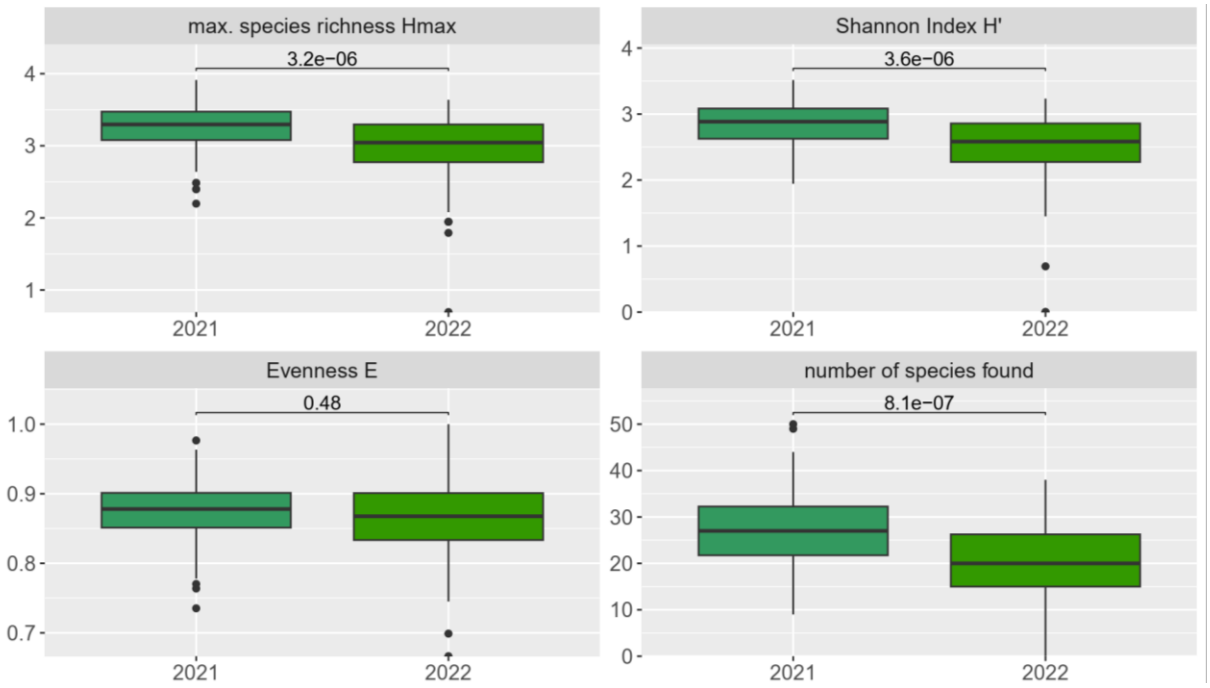

Figure 16: Hmax, H' and species richness are significantly higher in 2021 than in 2022 in ecological farming (n_{2021} = 83, n_{2022} = 80), evenness does not differ significantly

Fields that have been cultivated organically for a longer period of time and therefore have not been treated with chemical agents show a higher Shannon Index than those that have only recently been cultivated organically (Figure 17).

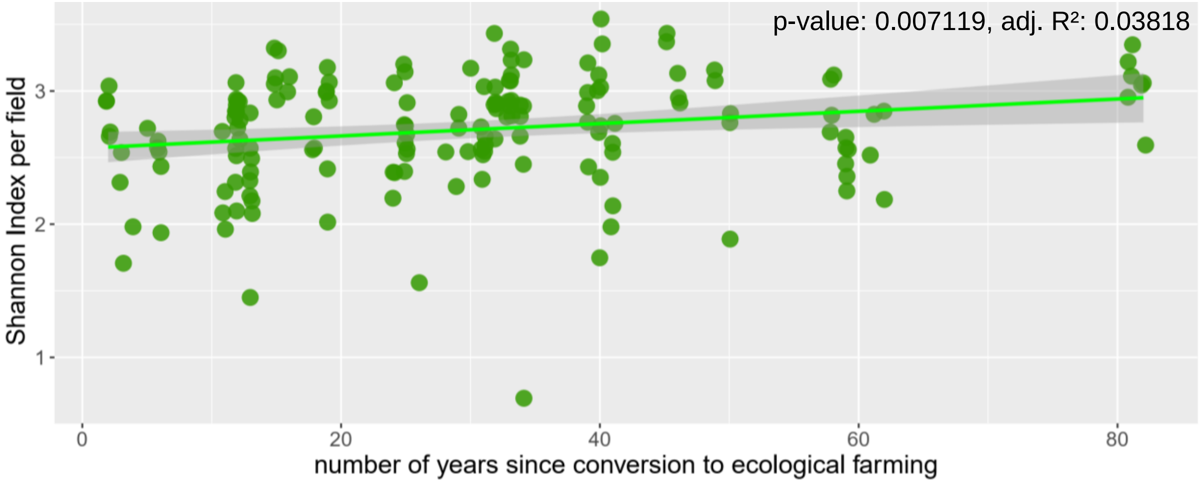

Figure 17: Shannon Index is significantly higher when fields are farmed ecologically for a longer time (n = 163)

3.1.2 Comparison of the years 2016 to 2022 within the data set of Kraichgau Korn

The Shannon Indices of the data set from the field weed championship from 2016 to 2019 are each significantly higher than those of the fields sampled in 2021 and 2022 as part of this study (Figure 18). The values between these two years also differ significantly, but the difference is similar to the data set of the ecological fields. The median Shannon Index is 2.1320 in 2021 and 1.8914 in 2022, which makes a difference of 0.2406. The mean Shannon Index is 2.2278 in 2021 and 1.9136 in 2022, which makes a difference of 0.3142.

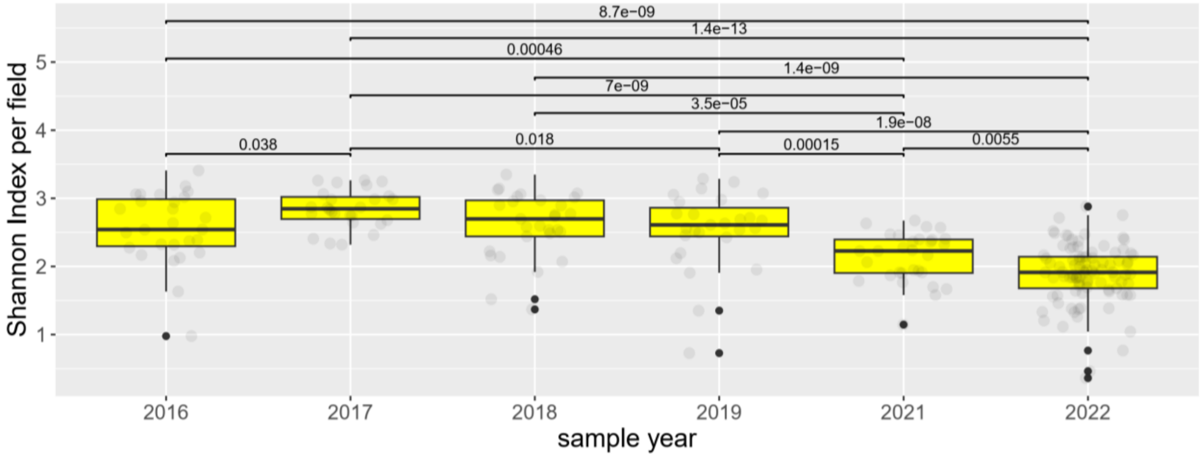

Figure 18: Shannon Index is significantly higher in the years 2016-2019 than in 2021 and 2022 in Kraichgau Korn fields ($n_{2016} = 27$, $n_{2017} = 26$, $n_{2018} = 29$, $n_{2019} = 27$, $n_{2021} = 30$, $n_{2022} = 93$)

3.1.3 Organic and conventional fields within the Linzgau Korn data set

Of the seven participating farms of Linzgau Korn, four farm their fields organically. This results in a small sample size of eight conventional and nine organic fields which were studied in 2022. Statistically significant differences between them can be found in all comparisons analysed: the ecological fields show a higher species richness as well as a higher Shannon Index, but lower yields (Figure 19).

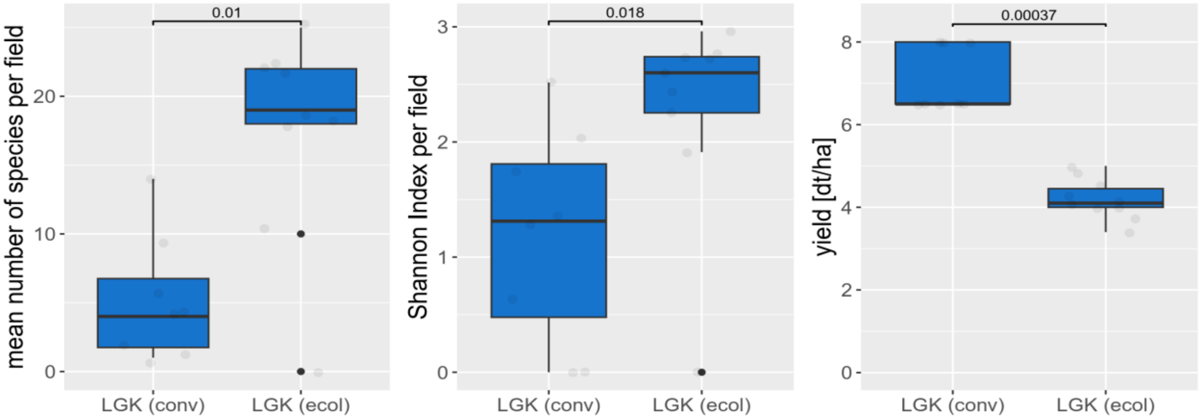

Figure 19: Within the Linzgau Korn data set, ecological fields have significantly higher number of species and Shannon Index than conventionally farmed LGK fields, but lower yields (n_{conv} = 8, n_{ecol} = 9)

In the years 2016-2019 ("field weed championship"), the difference in the mean number of species per field between conventional and organic fields within Linzgau Korn can be seen even more clearly than in 2022 (Figure 20). The total number of species found on all fields in each category was significantly lower in 2022 for conventional fields than in previous years, while that of organic fields peaked in 2022. In 2018 and 2019, five farms with 13 sites each were studied, two of which were organically farmed. This data is not available for 2016 and 2017; in 2022, the distribution was almost 50:50 (n_{conv} = 8, n_{ecol} = 9).

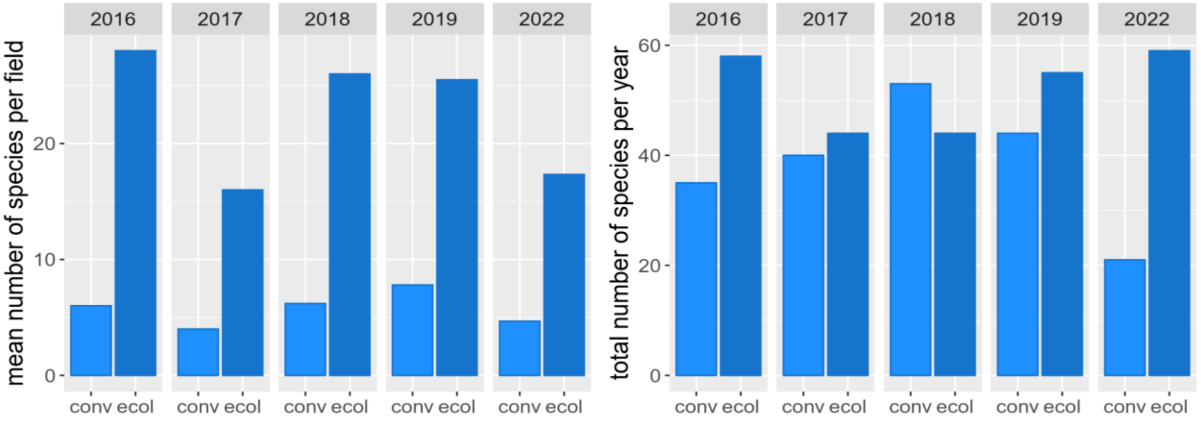

Figure 20: Ecological fields of LGK show higher values in the years 2016-2019 and in 2022 regarding mean and total number of species per field than conventional LGK fields

3.1.4 Integration of the additional data (IBL) into the data set

The additional data collected by the IBL (chapter 2.2.5) were analysed in comparison with the data collected in the scope of this study. Figure 21 takes into account only data from 2021 and 2022 and only crop fields to be able to compare the additional IBL and IBL FAKT data set. The Shannon Index of the ecologically certified fields with ecological varieties is significantly higher than all of the others. The difference between the transects on FAKT funded fields and the one that were not funded in 2021 is not significant, neither differs the Shannon Index between LGK fields and IBL or IBL FAKT fields. KGK shows a lower biodiversity according to the Shannon Index with a p-value of 0.015.

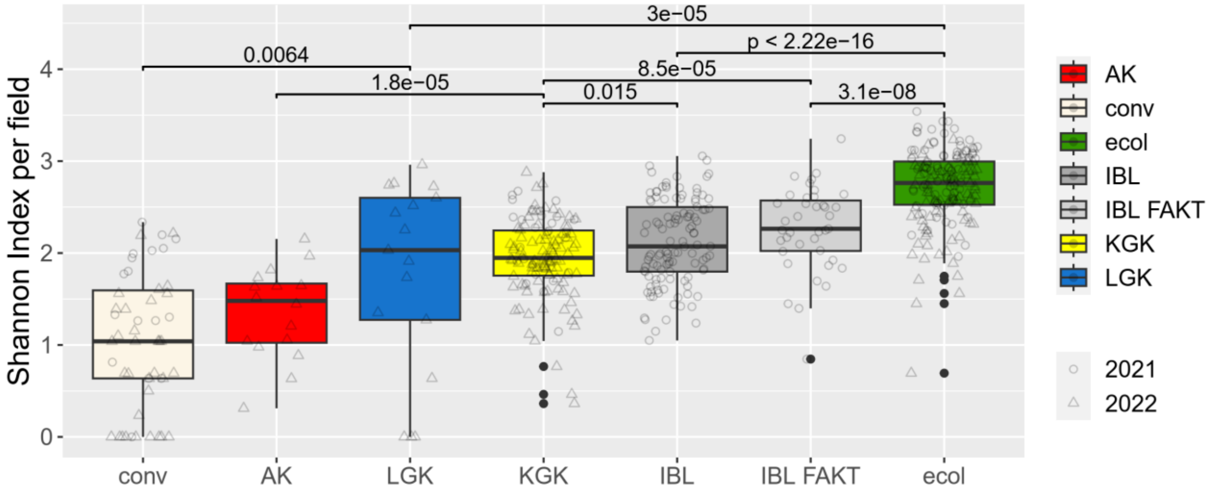

Figure 21: Comparison of the Shannon Index of the IBL data and FAKT/MEKA-funded IBL plots to the previously used data set shows, that both IBL data sets have higher Shannon Indices than the fields with intermediate cultivation methods (2021 + 2022, n_{conv} = 50, n_{AK} = 16, n_{LGK} = 17, n_{KGK} = 123, n_{IBL} = 115, n_{FAKT} = 39, n_{ecol} = 163), shape indicating sample year

3.1.5 Correlation between diversity, yield and external factors

How well a plant, both the cultivated crop and the accompanying flora, thrives depends on many different conditions. These include weather conditions such as precipitation, temperature and ground frost, as well as severe weather events. Soil quality, for example the pH value, the content of humus and organic carbon in the soil and nutrient levels, also have a major influence. Farmers must cultivate and manage their fields in the best possible way according to the given conditions. They can influence this in various ways: Fertilization, as well as the type and depth of tillage, the choice of variety and crop rotation, sowing time and seed rate, and of course the treatment of diseases or pests using mechanical, natural or chemical methods.

To assess the underlying correlations, I visualized them in a correlation plot (Figure 22).

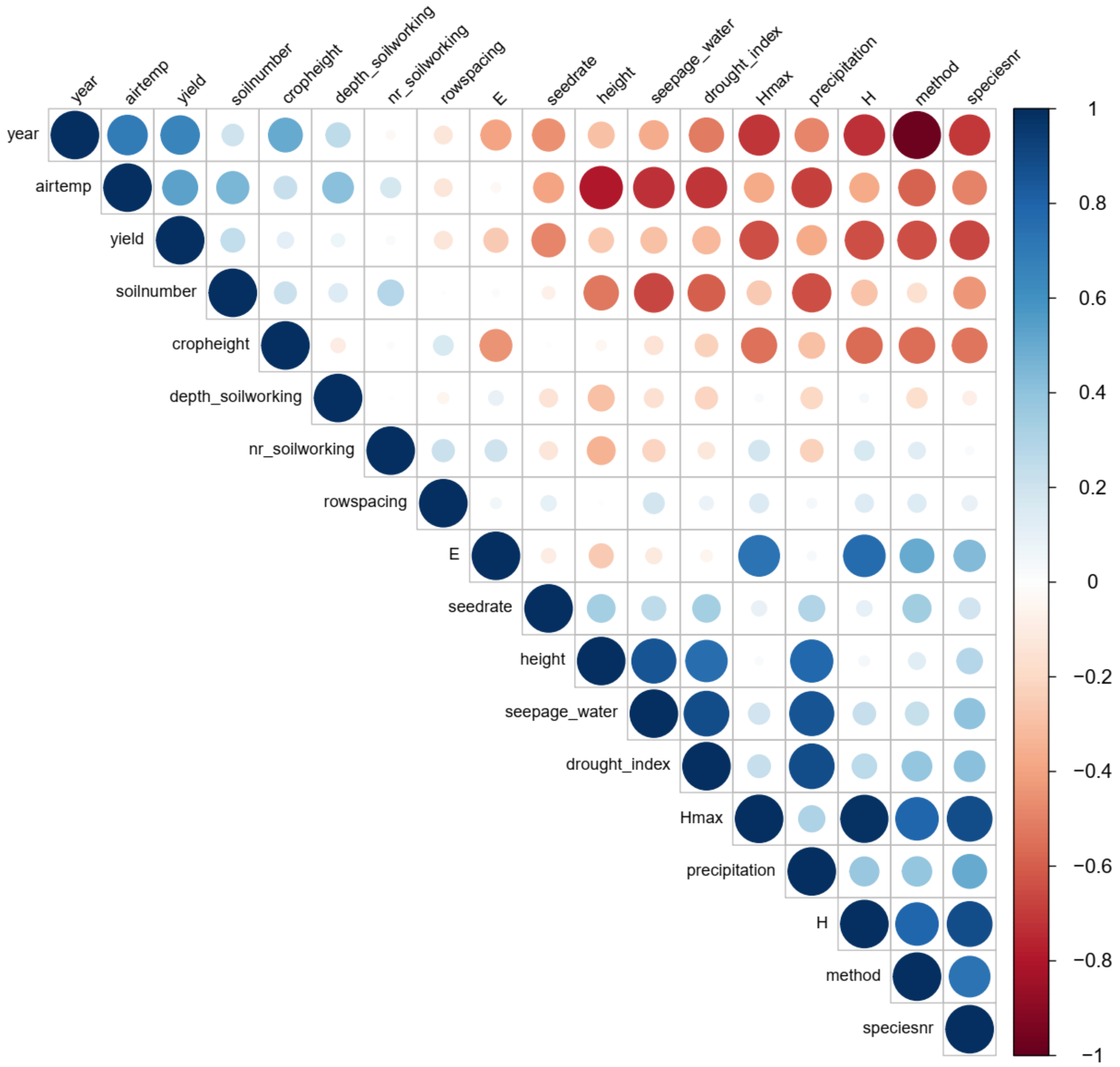

Figure 22: Correlation matrix (ordered by First Principle Component) displays the correlation of all studied factors

Then, I employed Principal Component Analysis (PCA) as a pivotal technique to distil complex patterns from our data set and find underlying structures. PCA is a common dimensionality reduction method used to condense the multitude of variables in a data set into a smaller set of uncorrelated components while preserving the majority of the original variance. It was used to find the features driving the variability within my data and to visualize it appropriately.

The data set contains 370 individuals and 29 variables. The first two dimensions express 45.5 % of the total data set inertia. The first dimension (36.67 %) is characterized by the farming method and weather correlated variables, mainly drought. The second dimension (8.83 %) is dominated by the month in which the vegetation data was sampled and soil values, especially the quantity of humus and C_{org} available. Graphically visualized in Figure 23 we can see that there is a slight difference between the two sample years in the ecological data set. They also have a high heterogeneity in their dissimilarity patterns. The LGK data set is very similar to the ecological fields. AK and KGK overlap only partly with the them and not at all among each other. The two sample years can be clearly distinguished when looking at the conventionally farmed fields, clustering in two small groups within the KGK ellipse.

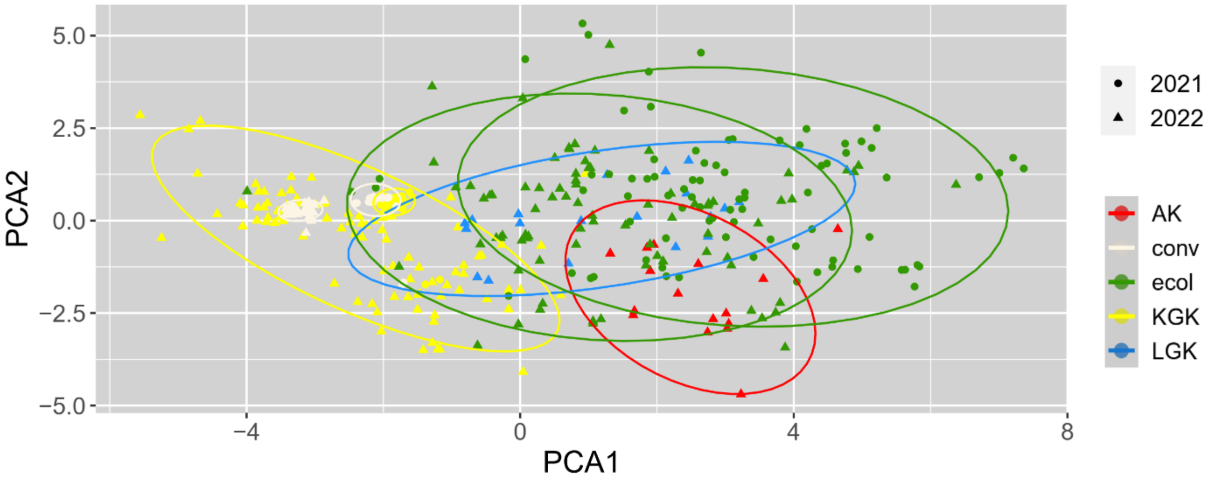

Figure 23: PCA Graph of individual fields (n = 370), shape indicating sample year. Ecological fields show heterogenous dissimilarity patterns in a similar region as LGK. Conventional fields fit into the same pattern as KGK, which has only little overlap with ecological and LGK fields and none with Albkorn fields.

As this statistical analysis is only an approximation, the influences of all individual factors on the Shannon Index are analysed separately in the following chapters.

3.1.6 Influence of height, temperature and precipitation on diversity

As some of the farming communities operate very regionally, the fields analysed differ in terms of the altitude at which they are located. For this reason, and because the fields are distributed throughout Baden-Württemberg and thus extend over different climatic regions, temperature and precipitation vary greatly in some cases. The fields on the Swabian Alb, to which Albkorn is limited, are located at the highest altitude. The part of the Kraichgau region close to Heidelberg, where the randomly selected conventional fields and the conventionally farmed fields of the Kraichgau Korn farmers are located, is the lowest at 95 m above sea level.

Within the Kraichgau Korn fields, there is a significant tendency of a decreasing Shannon Index the higher the analysed fields are located (p-value = 0.0002609, adj. R^2 = 0.09734). The ecological fields show the opposite effect: the higher the fields lie, the higher the Shannon Index is (adj. R^2 = 0.085, p-value = 0.0001429). Linzgau Korn (p-value = 0.6719, adj. R^2 = -0.05356), Albkorn (p-value = 0.4264, adj. R^2 = -0.02242) and conventional fields (p-value = 0.05143, adj. R^2 = 0.05753) show no significant tendencies (see Figure).

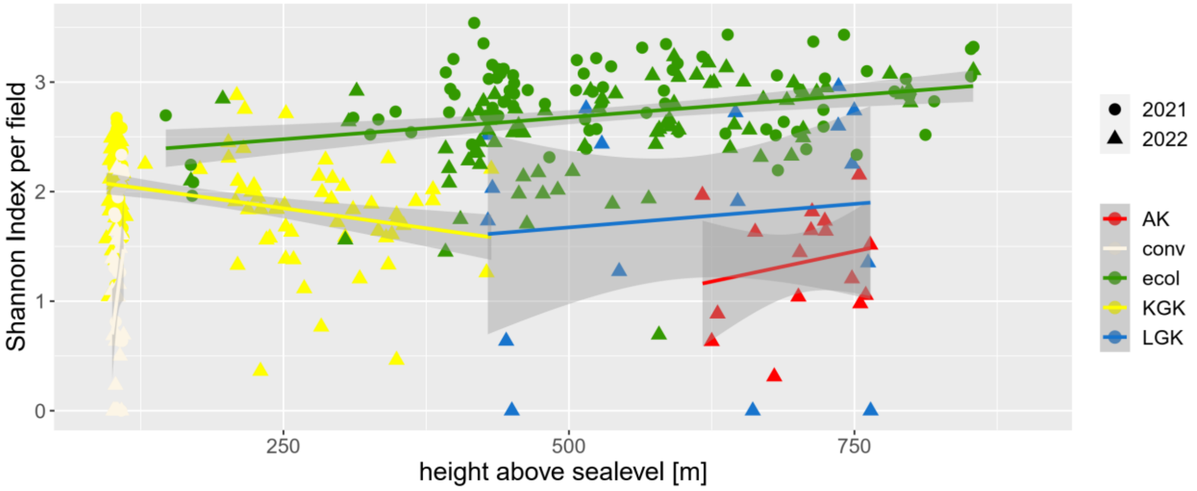

Figure 24: Influence of height on Shannon Index is only significant for ecological and KGK fields, but in different directions (n_{conv} = 50, n_{AK} = 16, n_{LGK} = 17, n_{KGK} = 123, n_{ecol} = 163), shape indicating sample year

Precipitation (Figure 25) shows a significant trend only in organic farming (p-value = 3.695e-08, adj. R^2 = -0.1669), where the Shannon Index increases with more rainfall. The trends are not significant for Linzgau Korn (p-value = 0.6739, adj. R^2 = -0.05373), Kraichgau Korn (p-value = 0.8281, adj. R^2 = -0.00787), Albkorn (p-value = 0.1914, adj. R^2 = 0.0557) and conventional cultivation (p-value = 0.976, adj. R^2 = -0.02081).

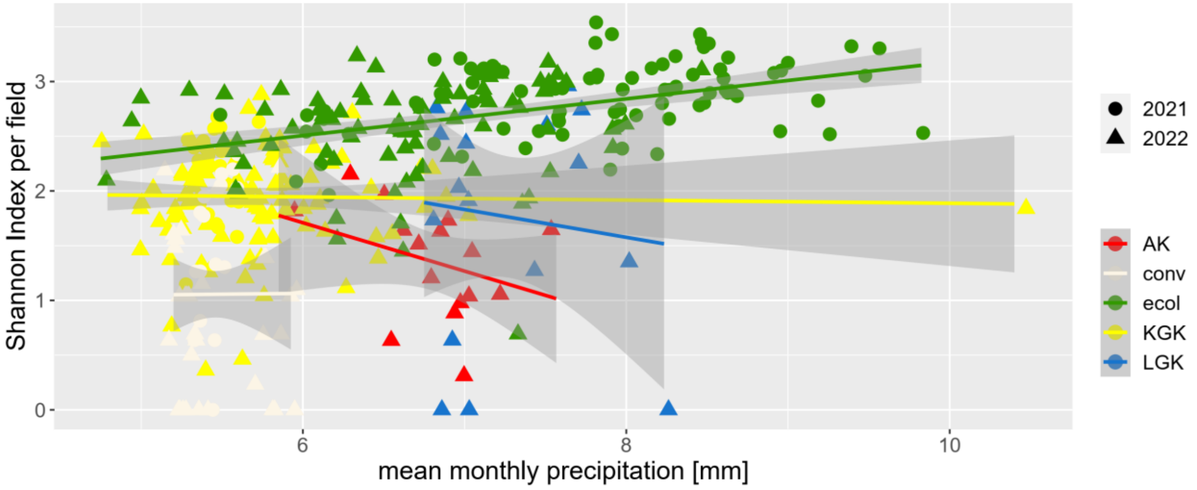

Figure 25: Influence of precipitation on the Shannon Index is only significant for organic farming, where higher Shannon Indices are found on fields with more precipitation (n_{conv} = 50, n_{AK} = 16, n_{LGK} = 17, n_{KGK} = 123, n_{ecol} = 163)), shape indicating sample year

A similar picture applies to the drought index (Figure 26): In addition to organic farming (p-value = 8.072e-06, adj. R^2 = 0.1112), conventional farming (p-value = 0.0002779, adj. R^2 = 0.227) also shows a significant trend, Linzgau Korn (p-value = 0.8402, adj. R^2 = -0.06368), Kraichgau Korn (p-value = 0.1873, adj. R^2 = 0.006178) and Albkorn (p-value = 0.06019, adj. R^2 = 0.1749) did not.

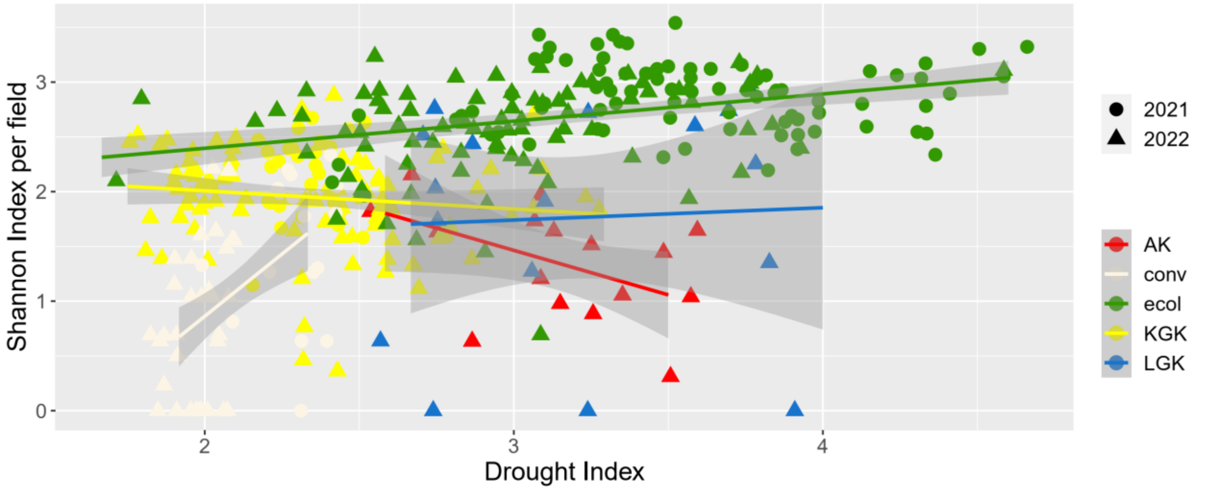

Figure 26: Shannon Index rises significantly with a higher drought index in organic and conventional farming (n_{conv} = 50, n_{AK} = 16, n_{LGK} = 17, n_{KGK} = 123, n_{ecol} = 163)), shape indicating sample year

The temperature on the Swabian Alb has lower maximum values than in other regions of Baden-Württemberg, but also fluctuates less. The temperature only varies a few °C and no significant influence on the Shannon Index is detectible (max. annual air temperature: p-value = 0.1603, adj. R^2 = 0.07398, mean annual air temperature: p-value = 0.1569, adj. R^2 = 0.07618, min. annual air temperature: p-value = 0.5516, adj. R^2 = -0.04368). Within the ecological fields, Shannon Index decreases significantly at higher temperatures, but only to a certain degree. The lower the minimum annual air temperature, the lower is the Shannon Index on that field (max. annual air temperature: p-value = 1.165e-08, adj. R^2 = 0.1785, mean annual air temperature: p-value = 3.103e-07, adj. R^2 = 0.1452, min. annual air temperature: p-value = 0.000921, adj. R^2 = 0.06032). The Kraichgau is the warmest region with many fields in regions with a maximum annual air temperature of 18 °C and above. The only significant trend can be observed when looking at the minimum annual air temperature: the higher the temperature gets, the lower is the corresponding Shannon Index (max. annual air temperature: p-value = 0.6905, adj. R^2 = -0.006938, mean annual air temperature: p-value = 0.2691, adj. R^2 = 0.001903, min. annual air temperature: p-value = 5.486e-05, adj. R^2 = 0.1191). The region around Lake Constance, where the Linzgau Korn fields are located, has relatively low minimum annual air temperature, but none of the three graphs show significant tendencies (max. annual air temperature: p-value = 0.6446, adj. R^2 = -0.05114, mean annual air temperature: p-value = 0.3859, adj. R^2 = -0.0128, min. annual air temperature: p-value = 0.8177, adj. R^2 = -0.06277) (Figure 27).

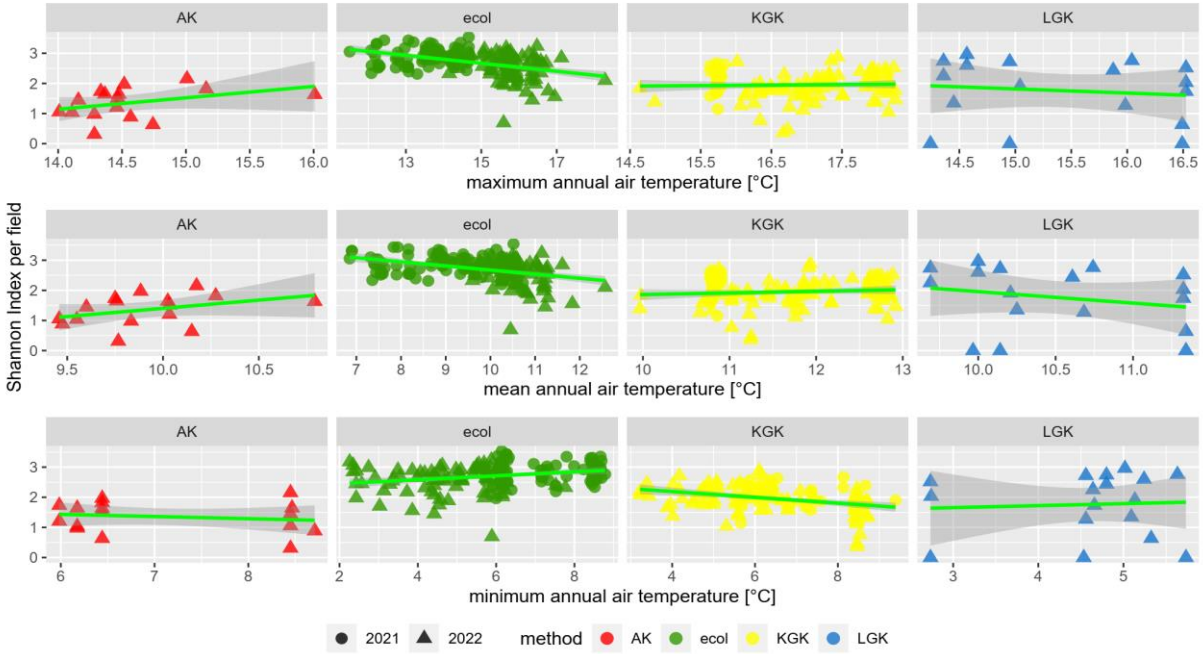

Figure 27: Influence of maximum, mean and minimum annual air temperature [°C] on Shannon Index, mean values of the mean monthly values (n_{AK} = 16, n_{LGK} = 17, n_{KGK} = 123, n_{ecol} = 163)), shape indicating sample year

As some plants require frost to induce germination, I analysed which of the fields were exposed to frost (monthly mean of the min. air temperature < 0 °C in at least one month of the corresponding year, Figure 28). The conventional fields have all been exposed to frost in 2021, but only one in 2022. The ones that have been exposed to frost have a significantly higher Shannon Index than the ones who have not. On the Kraichgau Korn fields, this effect cannot be seen: the only frost events occurred in 2021, while in 2022 many fields were not exposed to frost, but there is no significant difference between the two groups. Looking only at Kraichgau Korn data from 2022, the fields that were exposed to frost show a significantly lower Shannon Index (p-value 0.00028) than the other ones, contrary to the conventional fields.

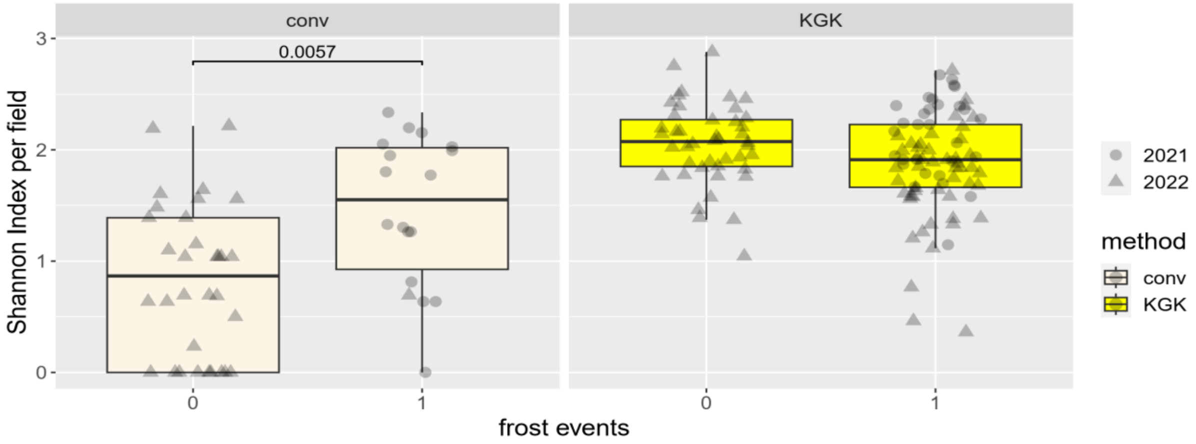

Figure 28: Shannon Index is significantly higher in conventional farming when there was a frost event (1) in the corresponding year (n_{conv0} = 32, n_{conv1} = 18, n_{KGK0} = 44, n_{KGK1} = 81), shape indicating sample year

3.1.7 Influence of soil type on diversity

In Germany, the measure of the productivity of agricultural land or yield capacity of agricultural soils is assessed using a comparative value ranging from 0 (very low) to 100 (very high). In Figure 29, the influence of this value on the Shannon Index is assessed. Here, too, organic farming (p-value = 0.0007514, adj. R² = 0.1209) and Kraichgau Korn (p-value = 0.01212, adj. R² = 0.06964) show opposing trends: while the Shannon Index for Kraichgau Korn increases with increasing soil number, it decreases for organic farming. The trends observed for Linzgau Korn (p-value = 0.05679, adj. R² = 0.2528) and Albkorn (p-value = 0.929, adj. R² = -0.1979), both with very small sample sizes, are not significant.

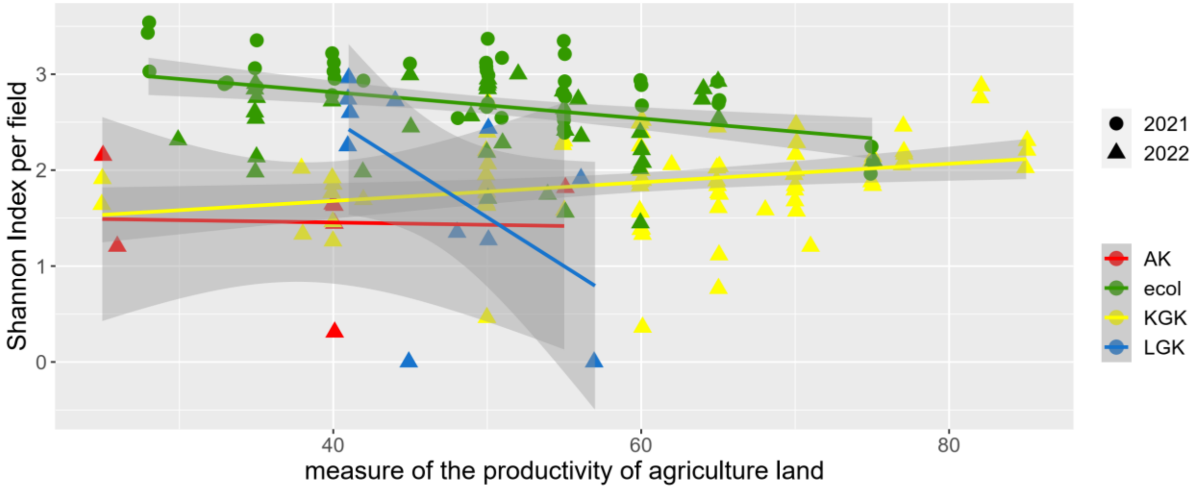

Figure 29: Influence of the measure of the productivity of agricultural land on the Shannon Index show opposing trends for KGK and organic farming (n_{AK} = 7, n_{LGK} = 12, n_{KGK} = 78, n_{ecol} = 86), shape indicating sample year

The farmers indicated the predominant soil type on their fields in the surveys. In order to increase the sample size of the soil types, they were categorized into the five soil type groups analogous to the Agricultural investigation and research institutes LUFA (Geologischer Dienst NRW, 2019), 1 being very sandy soils and 5 being clayey loam and clay. In both farming methods analysed, sandy soils clearly achieved the highest Shannon Index (Figure 30). In ecological farming, soil type group 1 differs significantly from group 4 (p-value = 0.0063) and 5 (p-value = 0.00095). In KGK, soil type group 1 differs significantly from group 2 (p-value = 0.024) and 5 (p-value = 0.027) and group 2 from group 4 (p-value = 0.021).

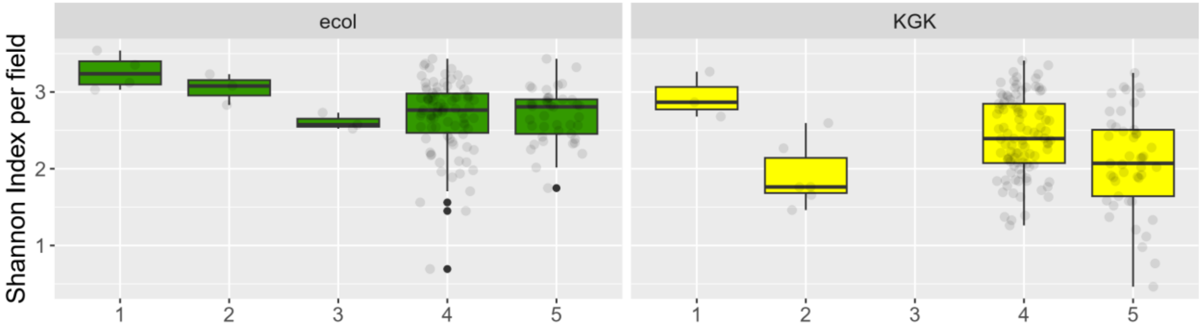

Figure 30: Shannon Index is slightly higher on sandy soils than on loam and clay. Soil type groups (analogous to LUFA (Geologischer Dienst NRW, 2019)), (n_{ecol} = 138, n_{KGK} = 155)

There is no significant influence of the pH value on Shannon Index in any of the analysed farming methods (ecol.: p-value = 0.2155, adj. R² = 0.006213, LGK: p-value = 0.5031, adj. R² = -0.03421, KGK: p-value = 0.3928, adj. R² = -0.003538, AK: p-value = 0.4686, adj. R² = -0.03503, Figure 31).

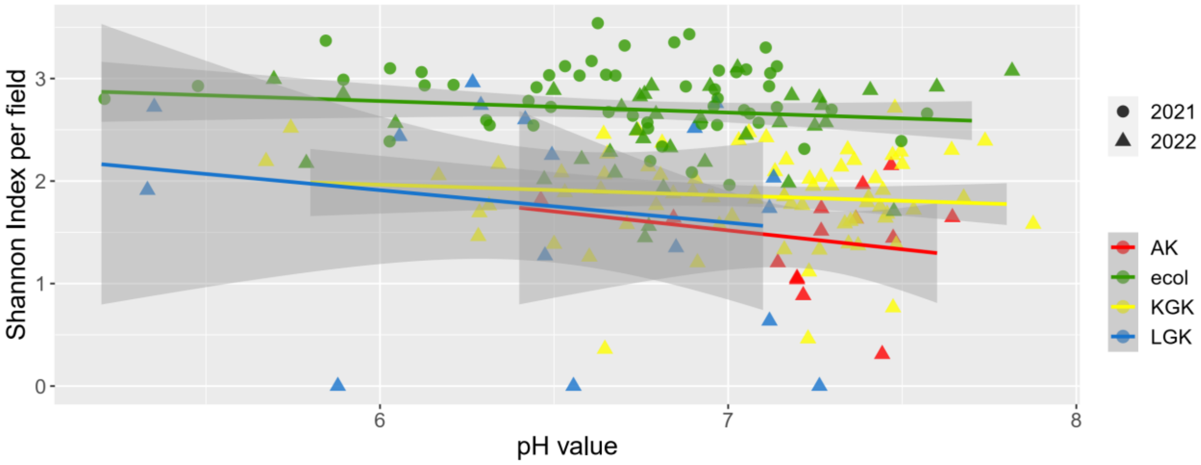

Figure 31: Influence of the pH value on the Shannon Index is not significant in any of the analysed farming methods (n_{ecol} = 161, n_{KGK} = 80, n_{LGK} = 16, n_{AK} = 12), shape indicating sample year

3.1.8 Influence of farming practices on diversity

Besides factors that can hardly be influenced, such as weather and farm location, there are several technical methods that a farmer can use to influence what grows in his field. At the very beginning of the cultivation cycle, for example, these include the chosen crop rotation, the variety and the sowing density. The way and intensity with which the field is cultivated over the course of the year also influences the growth of the crop and its wild associates.

The influence of row spacing at sowing has no significant influence on the Shannon Index in ecological farming (Figure 32).

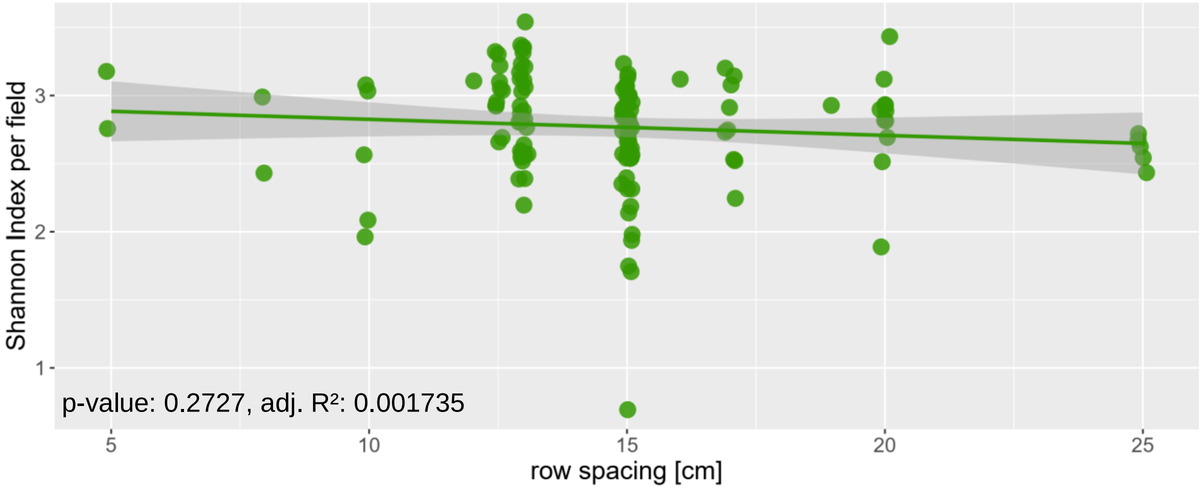

Figure 32: There is no significant influence of row spacing on Shannon Index on ecological fields (n = 124)

The seed rate also does not have a significant influence on the Shannon Index in ecological farming (Figure 33).

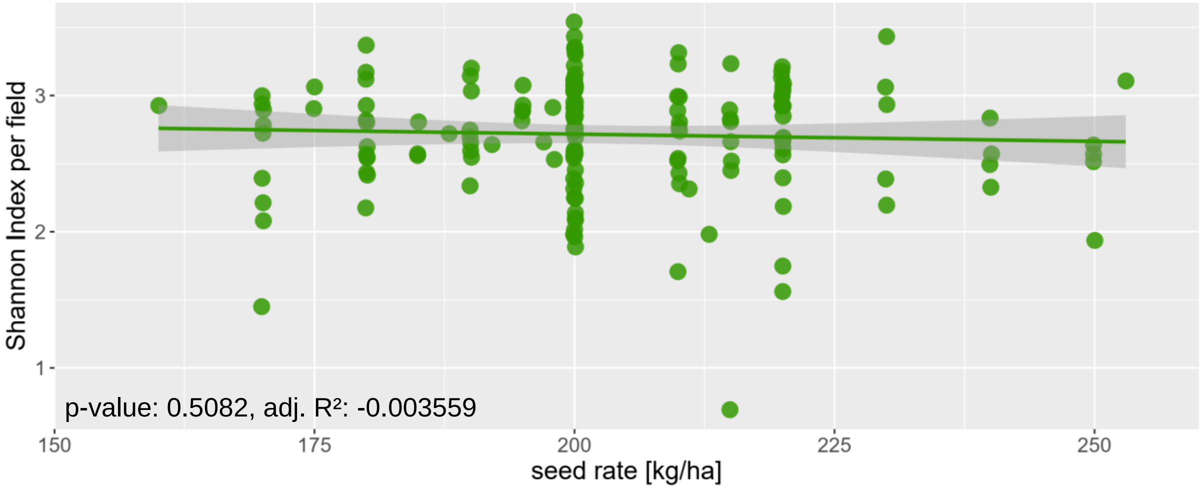

Figure 33: There is no significant influence of the seed rate on Shannon Index on ecological fields (n = 160)

Farmers could either state how often they would work the soil in advance in the online survey or provide the actual number afterwards. If farmers indicated 1-2 or 2-3 times, this was noted as 1.5 or 2.5 respectively. Within the group of organic farmers, the number of currying or hoeing operations does not have a significant influence on the Shannon Index, as the comparison of neither of numbers of operations gives a p-value < 0.05 (Figure 34).

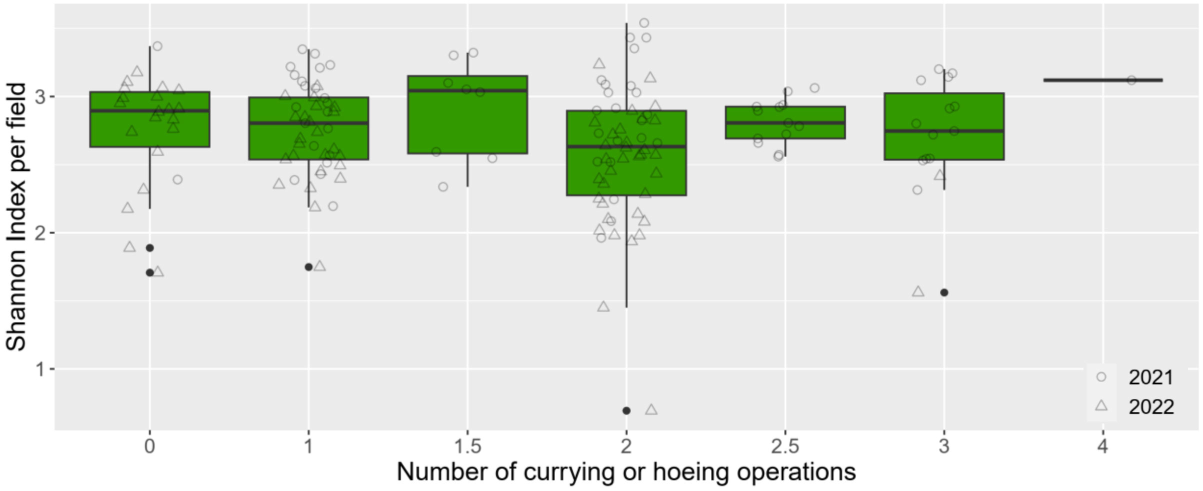

Figure 34: An influence of the number of currying or hoeing operations on the Shannon Index of each field was not determined (n = 161), shape indicating sample year

The maximum depth of soil tillage as indicated by the farmers also has no significant influence on the Shannon Index in any of the studied cultivation methods (ecol: p-value = 0.5449, adj. R^2 = -0.007746; KGK: p-value = 0.3261, adj. R^2 = -0.00003198; LGK: p-value = 0.6612, adj. R^2 = -0.09662; AK: p-value = 0.1231, adj. R^2 = 0.1186, Figure 35).

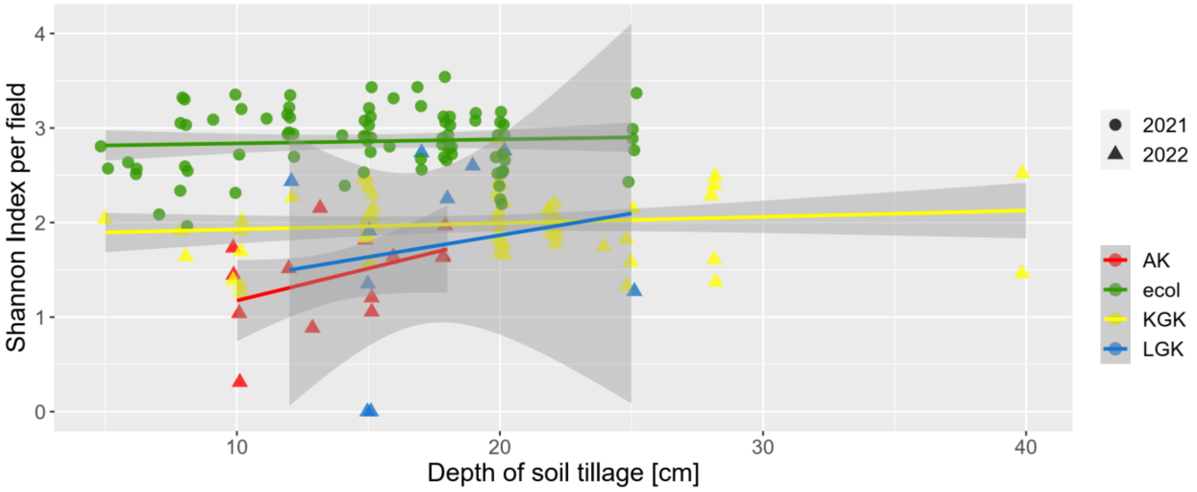

Figure 35: There is no significant influence of the depth of soil tillage on Shannon Index (n_{AK} = 14, n_{LGK} = 11, n_{KGK} = 67, n_{ecol} = 83), shape indicating sample year

The differences in ploughed and unploughed fields show inconsistent results for organic farming and Kraichgau Korn (Figure 36): while Shannon Index of unploughed fields is significantly lower in KGK (p-value 0.0048), no significant differences can be found in ecological farming (p-value 0.1).

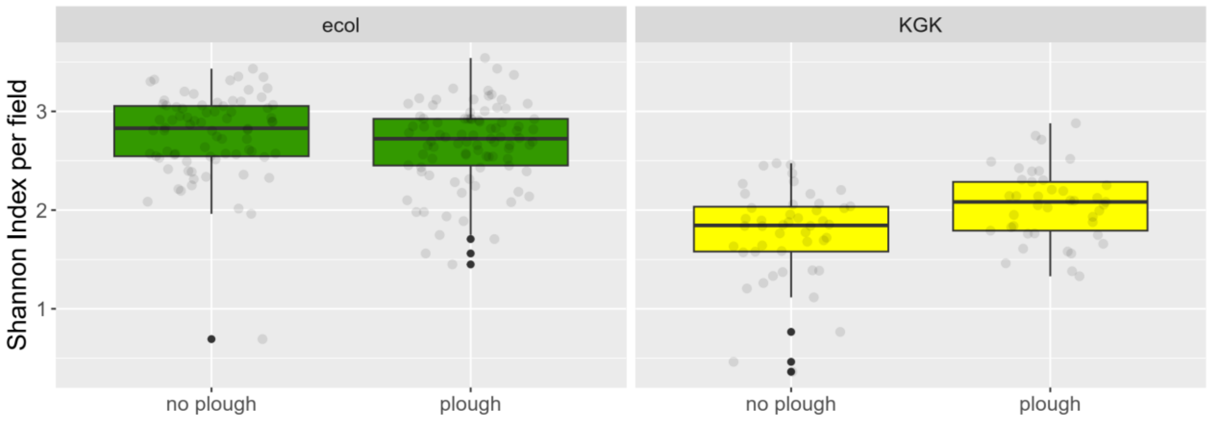

Figure 36: Unploughed fields showed significantly lower Shannon Index in KGK, while in ecological farming, no significant difference was determined (n_{ecol} = 164, n_{KGK} = 88)

Since different crops reach very different heights and have different nutrient requirements, this results in corresponding differences in the flora accompanying the field. Figure 37 shows an overview of the average number of species per field for the cultivated crops. In the case of Albkorn and Linzgau Korn, weed in wheat fields performed slightly better than in barley. In organic cultivation it was the other way around, as well as in conventional cultivation, but there both crops were surpassed by weed presence in spelt fields. In the ancient cereals einkorn and emmer, as well as in rye, which are only cultivated by Kraichgau Korn farmers, weed performed slightly better than in spelt and wheat, but far worse in barley fields. A dependence of the species diversity on the crop species and cereal variety used is difficult to determine due to the high number of different varieties and variety combinations, respectively the resulting small sample per variety. Therefore, significance values were not calculated.

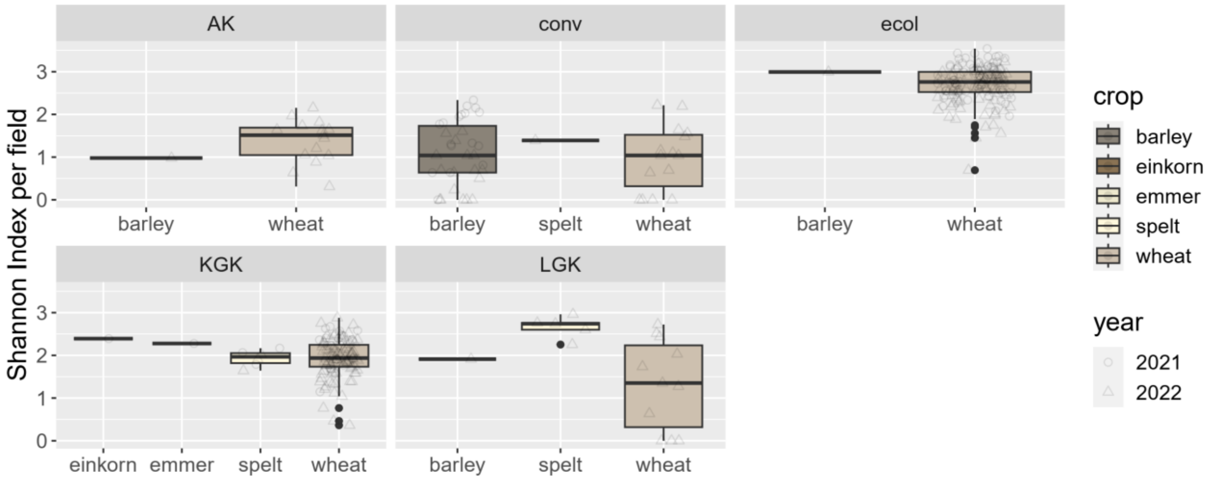

Figure 37: Shannon Index varies between the different crops in each cultivation method (AK: n_{barley} = 1, n_{wheat} = 15; conv: n_{barley} = 34, n_{bspelt} = 1, n_{wheat} = 15; ecol: n_{barley} = 1, n_{wheat} = 162; KGK: $n_{einkorn}$ = 1, n_{emmer} = 1, n_{bspelt} = 6, n_{wheat} = 115; LGK: n_{barley} = 1, n_{bspelt} = 5, n_{wheat} = 1), shape indicating sample year

The sample for the varieties used is very small in some cases: several varieties were grown on only one field. Figure 38 shows the average Shannon Index of the fields per cultivated variety. Statistical significance was not tested due to the small sample size. On average, the variety "Alauda" achieved the highest values, while the maximum value within the study was achieved by a field with the "Wiwa" variety. The lowest Shannon Indices were achieved by fields of the varieties "Oberkulmer Rotkorn", "Ponticus" and "Genius". However, these three varieties also had the widest range between the highest and lowest Shannon Index. If more than three varieties were grown in one field, it was designated as a variety mix. However, these variety mixtures, some of which consist of up to 39 varieties (population varieties), do not show considerably higher values compared to many other organic varieties.

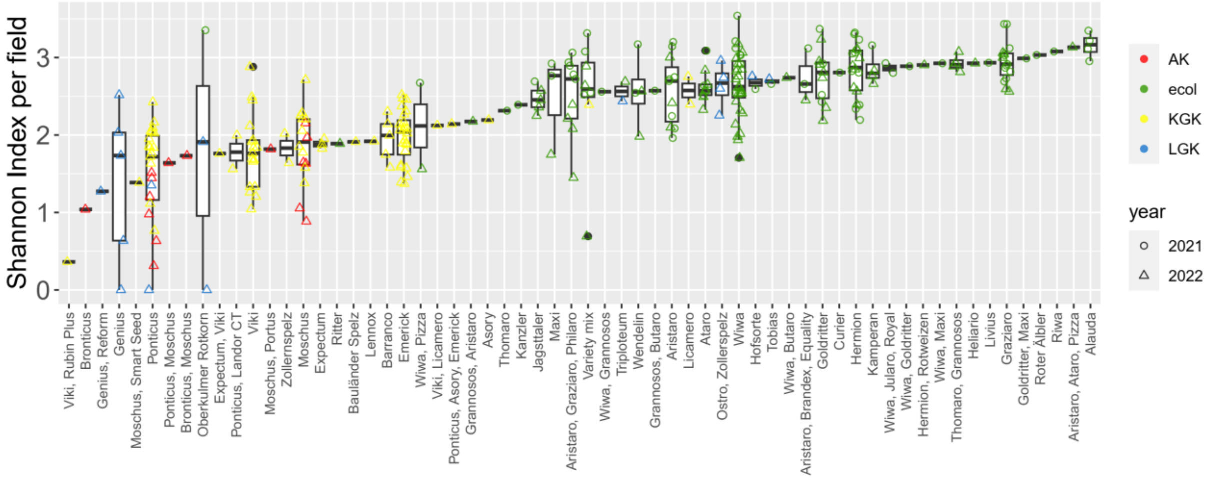

Figure 38: Shannon Index per cultivated crop variety varies, but clusters similar to the determined Shannon Index of each farming method. Colour indicating cultivation method, shape indicating sample year

To analyse the influence of the number of years of the crop rotation, the data set of organic farmers was used again (Figure 39). No significant differences were found (all p-values > 0.05).

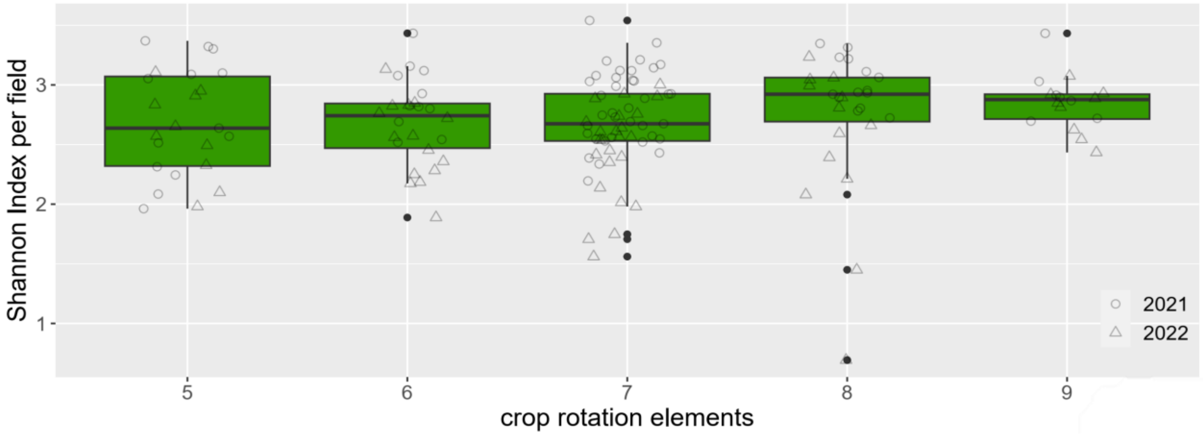

Figure 39: No significant influence of the number of years of the crop rotation on the Shannon Index could be found (n = 154), shape indicating sample year

3.1.9 Study design-implicated influences on diversity

All fields were mapped within a period of less than 1.5 months by a number of different mappers (see chapter 2.3.2). The influence of differing experience was reduced as far as possible by the study design but is still possible. Therefore, I analysed the influence of the number of mapping runs, the position of the transect, the measured crop height at the time of mapping and the influence of the mappers themselves on the Shannon Index. To achieve better comparability, only ecological fields from 2021 were considered for the following two analyses. In Figure 40 I use the example of 41 organic wheat fields to show that there is a slightly higher species diversity in transect A (parallel to field edge), as was also shown in other studies (see Discussion). However, in order not to expose the areas to additional stress by walking on them, the centre of the field was not examined in most cases.

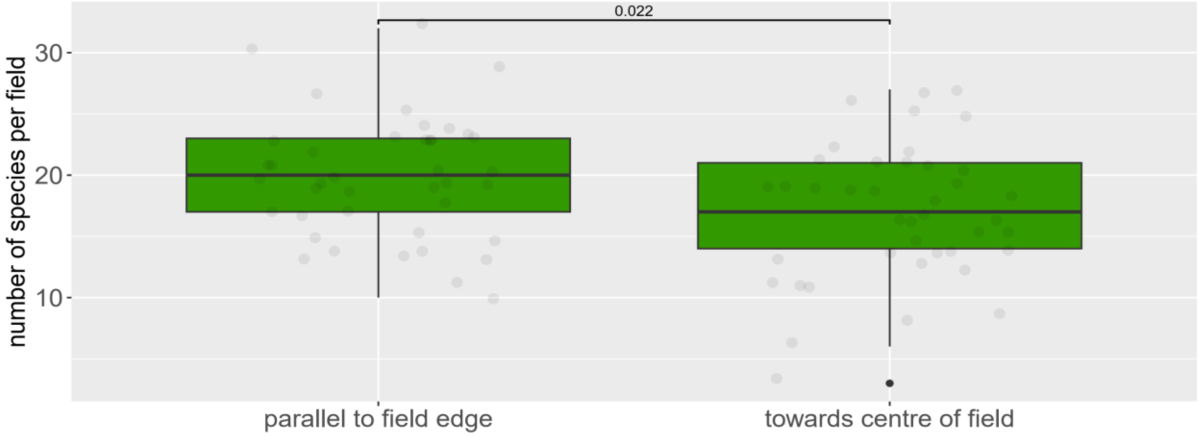

Figure 40: Number of species is higher in the transsect mapped parallel to the field edge than in the centre of the field (n = 41 fields, two inspections per field)

There is no significant influence on the number of species found on each field whether it was mapped just once by one person or by multiple mappers (Figure 41).

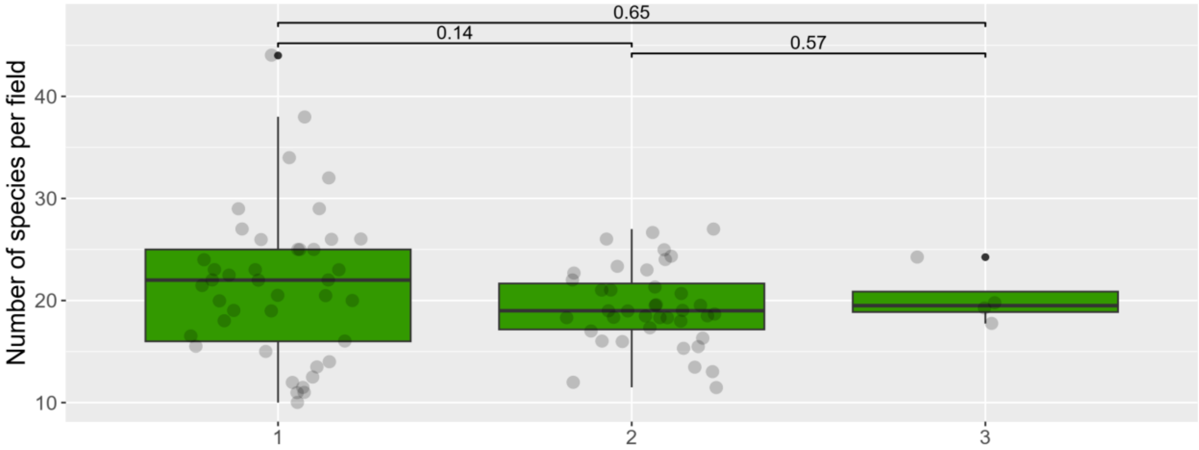

Figure 41: No significant difference in the number of species was found between the number of mapping passes (year 2021, n = 84)

Due to different varieties, site conditions and sowing times, the arable weed plants compete for light and nutrients to varying degrees. It was therefore investigated whether the height of the crop at the time of mapping has an influence on the Shannon Index (Figure 42). No significant effect was found for KGK, but the organic fields showed a decreasing Shannon Index with increasing cereal height.

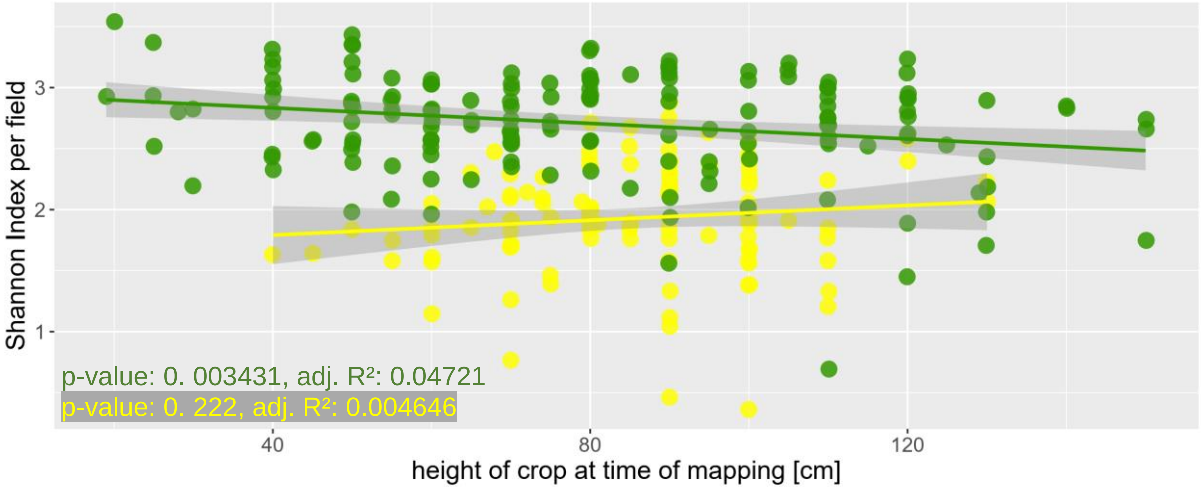

Figure 42: Shannon Index of ecological fields decreases significantly with increasing crop height at the time of mapping (green, n = 159), but KGK fields do not show a significant tendency (yellow, n = 111)

The small sample size makes it difficult to analyse the influence of the mappers on the biodiversity of the fields. High variations between the different mappers can be seen throughout all mapped fields, but many mappers only mapped very few fields (Figure 43).

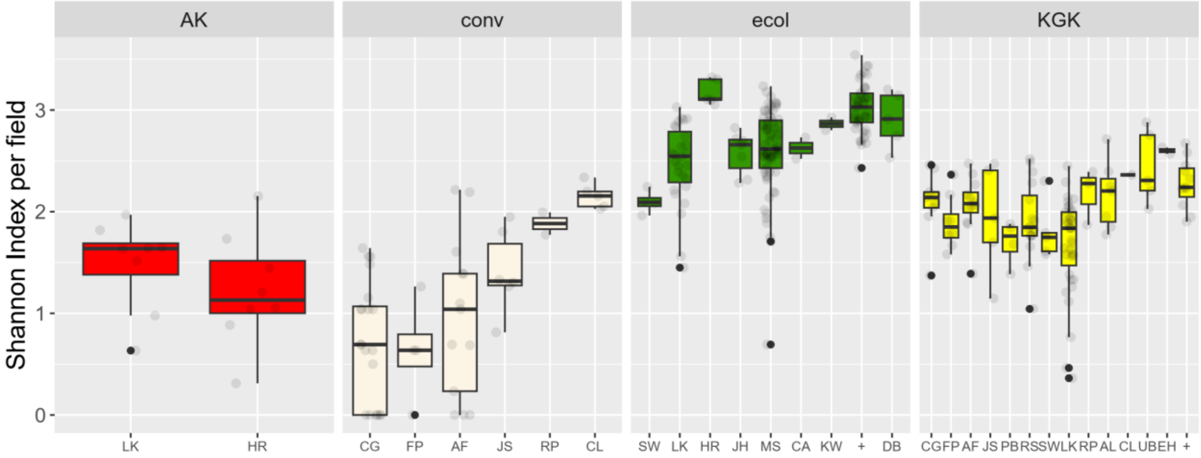

Figure 43: Shannon Index influences strongly between mappers, but multiple mappers is marked with a „+“

3.2 Comparison of yields

As already mentioned in the introduction, yield is a key factor both for the financial security of the farmer and for feeding the world's population. The following section therefore analyses how different factors affect yield. The yield of organically managed fields is significantly lower than that of all other fields (Figure 44). Linzgau Korn and Kraichgau Korn do not differ significantly. Albkorn, which also allows chemical inputs, has the highest yield on average.

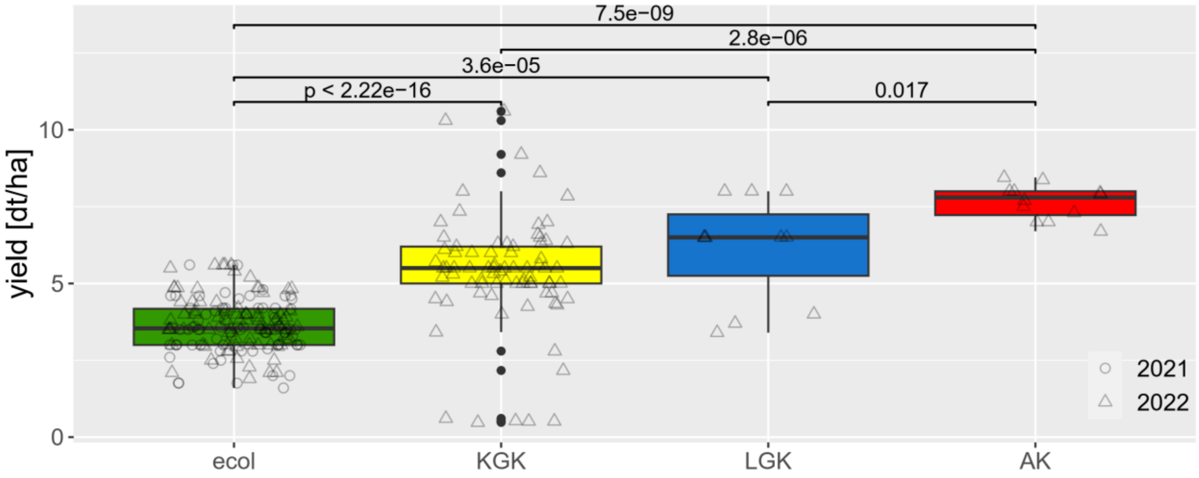

Figure 44: Yield in dt/ha per cultivation method, only wheat fields included (n_{ecol} = 161, n_{KGK} = 80, n_{LGK} = 18, n_{AK} = 13), shape indicating sample year

The yields decrease with increasing Shannon Index (Figure 45). However, this effect is not significant for AK (p-value = 0.6583, adj. R^2 = -0.07079) and KGK (p-value = 0.09743, adj. R^2 = 0.02274). A significant tendency can be seen in the organic fields (p-value = 0.01021, adj. R^2 = 0.03474), as well as in those of LGK (p-value = 0.04144, adj. R^2 = 0.1989).

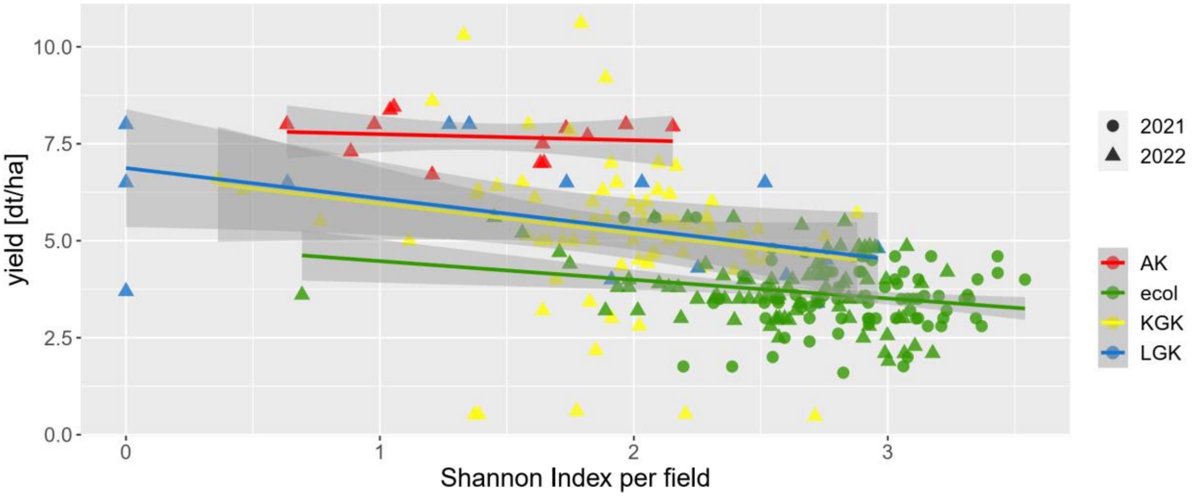

Figure 45: Decreasing yield with increasing Shannon Index per field is only significant for ecological and LGK fields. Colours indicating cultivation method (n_{ecol} = 161, n_{KGK} = 80, n_{LGK} = 17, n_{AK} = 13), shape indicating sample year

3.2.1 Yield differences within the ecological fields

Although there is no significant difference in Shannon Index between the organic farming standards (see Figure 15), there is a significant difference (p-value = 0.00011) in yield between the fields that were cultivated according to Demeter and Bioland (Figure 46). The fields that were cultivated according to Naturland guidelines show no significant differences to the other two, but can only be assessed with caution due to the very small sample size (n = 10).

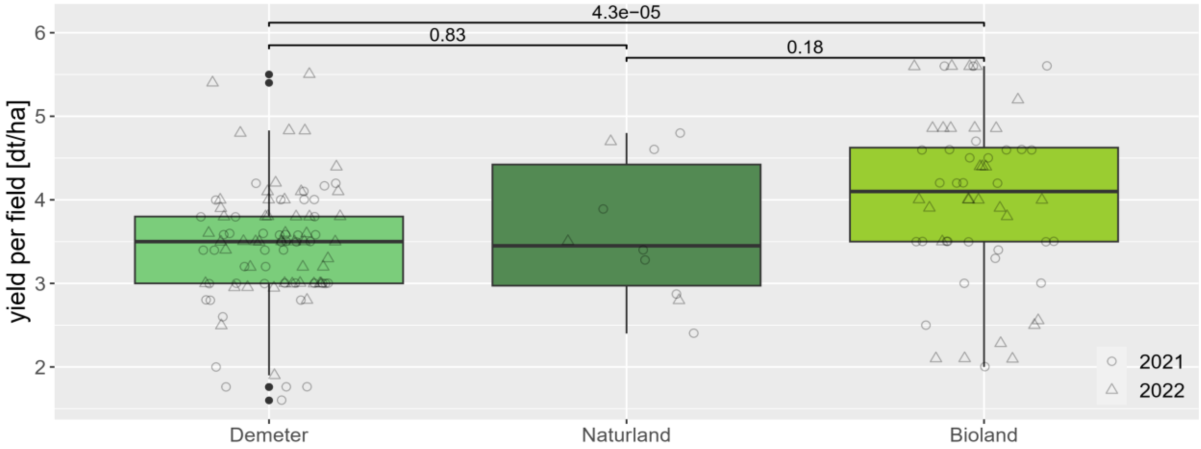

Figure 46: Comparison of yields per field in dt/ha per certification guideline in organic farming shows significantly lower yields for Demeter compared to Bioland ($n_{Demeter}$ = 197, $n_{Naturland}$ = 10, $n_{Bioland}$ = 56), shape indicating sample year

3.2.2 Influence of height, temperature and precipitation on yield

Within the Kraichgau Korn fields, there is a significant tendency of increasing yield the higher the analysed fields are located (p-value = 0.02958, adj. R^2 = 0.04719). The ecological fields show the opposite effect: the higher the fields lie, the lower the yield is (p-value = 0.001374, adj. R^2 = 0.05667). Linzgau Korn (p-value = 0.3235, adj. R^2 = 0.002639) and Albkorn (p-value = 0.8061, adj. R^2 = -0.08468) do not show any effects of height on yield (Figure 47).

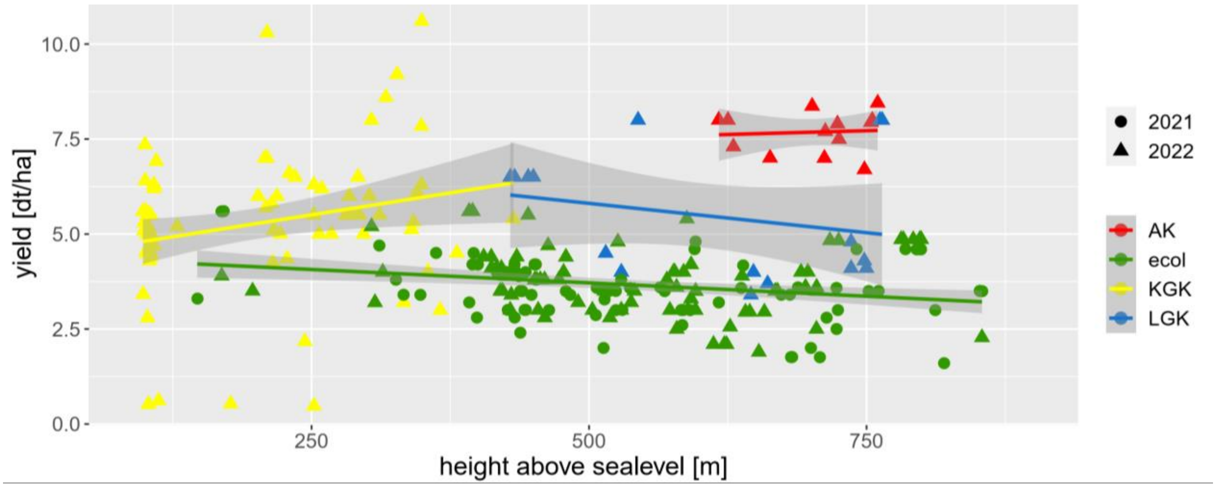

Figure 47: Influence of height on yield is significant for ecological and KGK fields, but with opposing effects (n_{ecol} = 161, n_{KGK} = 80, n_{LGK} = 18, n_{AK} = 13), shape indicating sample year

Almost none of the results of the comparison of yield with the development of air temperature are significant (Figure 48). Only in the case of mean annual air temperature does the yield increase significantly with increasing temperature (p-value = 0.01073, adj. R^2 = 0.0342).

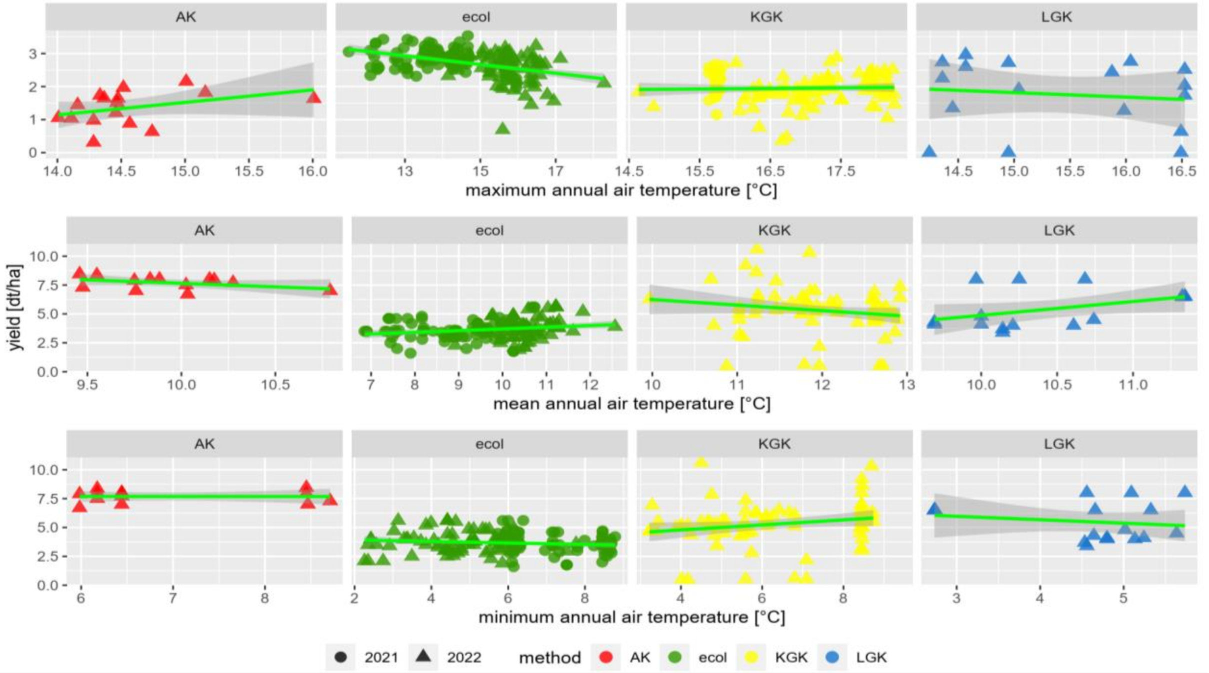

Figure 48: Influence of maximum, mean and minimum annual air temperature [°C] on yield, mean values of the mean monthly values (n_{ecol} = 161, n_{KGK} = 80, n_{LGK} = 18, n_{AK} = 13), shape indicating sample year

Kraichgau Korn (p-value = 0.03111, adj. R^2 = 0.04612) and ecological farming (p-value = 0. 006114, adj. R^2 = 0.04007) have significantly lower yields with increasing precipitation (Figure 49). Trends are not significant in Linzgau Korn (p-value = 0.2446, adj. R^2 = 0.02833) and Albkorn (p-value = 0.6408, adj. R^2 = -0.06856).

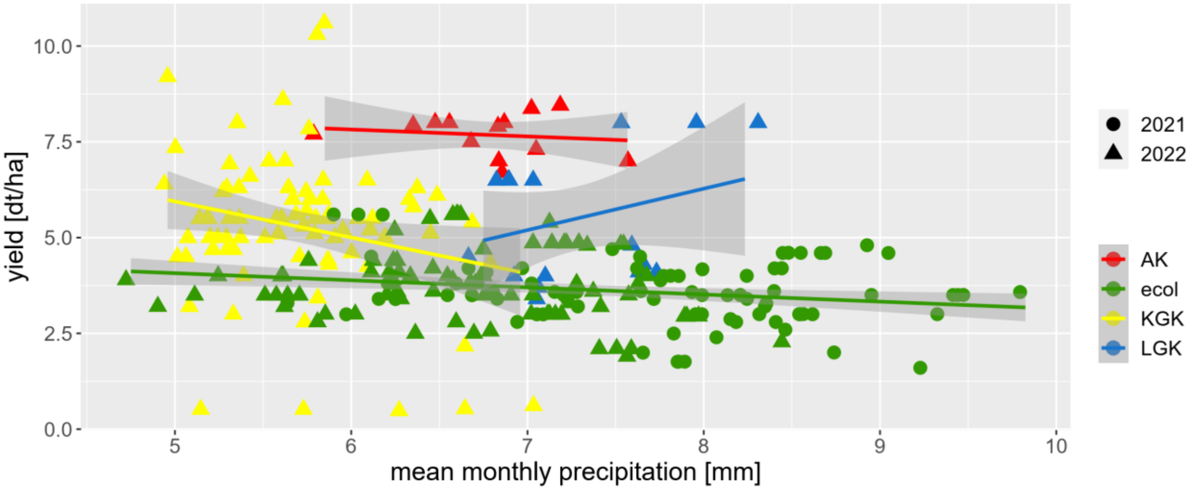

Figure 49: Yields are significantly lower on fields with more precipitation in ecological farming and KGK (n_{ecol} = 161, n_{KGK} = 80, n_{LGK} = 18, n_{AK} = 13), shape indicating sample year

The link between drought index and yields is only significant in organic farming, dry conditions appear to be connected with higher yields (p-value: 0.001723, adj. R² = 0.05385). Albkorn (p-value = 0.6406, adj. R² = -0.06852), Linzgau Korn (p-value = 0.8273, adj. R² = -0.06317) and Kraichgau Korn (p-value = 0.5443, adj. R² = -0.008028) do not show a significant trend (Figure 50).

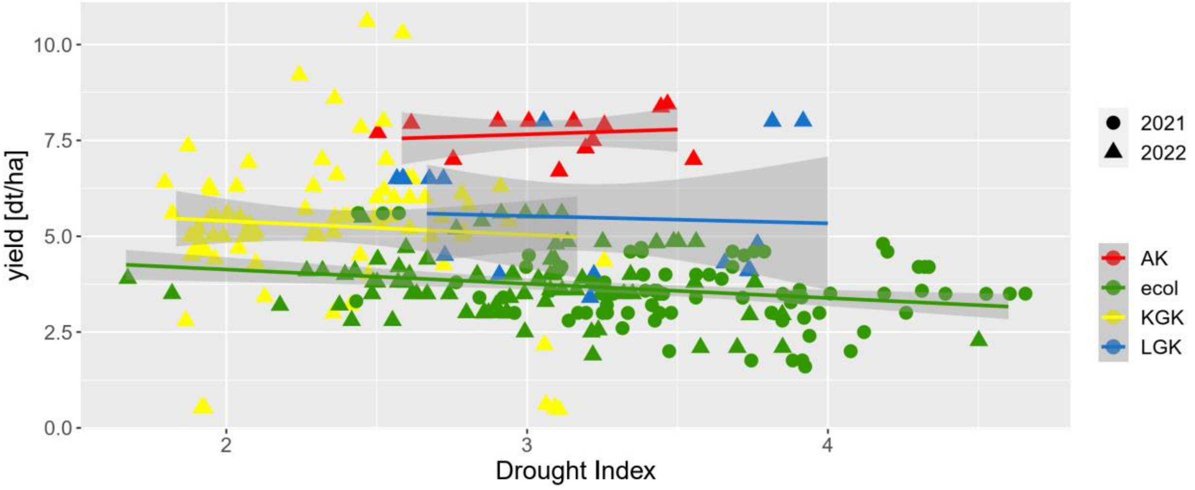

Figure 50: Influence of Drought Index on yield is only significant in organic farming, where lower yields are found in drier conditions (n_{ecol} = 161, n_{KGK} = 80, n_{LGK} = 18, n_{AK} = 13), shape indicating sample year

In the year 2022, there was significantly more yield on Kraichgau Korn fields that experienced frost than on the ones without frost events (Figure 51).

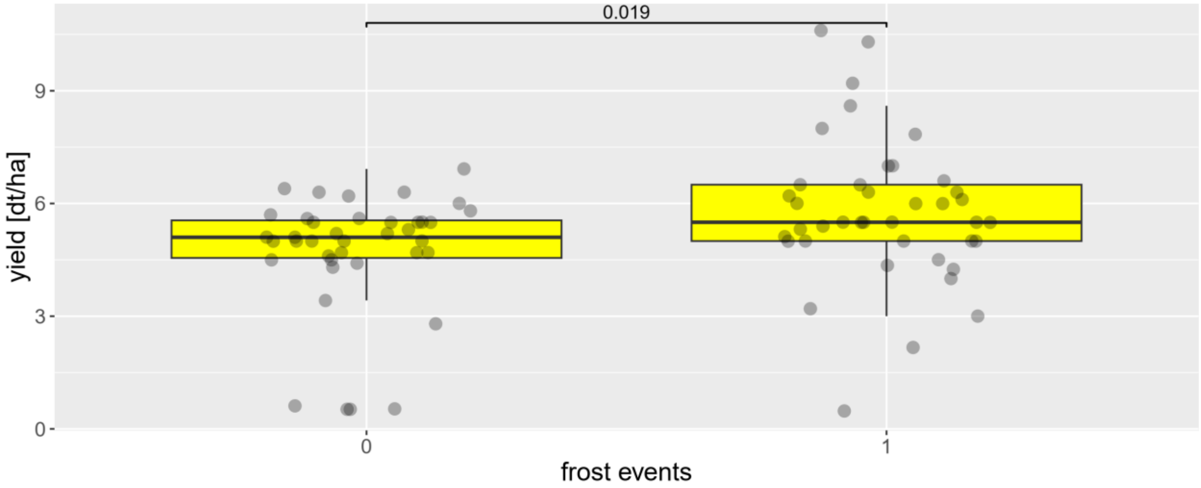

Figure 51: Yield is significantly higher when there was a frost event on KGK fields (2022, n_0 = 39, n_1 = 41)

3.2.3 Influence of soil type on yield

The predominant soil type of the farmer's fields was categorized into the five soil type groups analogous to LUFA (Geologischer Dienst NRW, 2019), 1 being very sandy soils and 5 being clayey loam and clay. There is barely a significant influence of the soil type on yield, but in ecological farming between soil type groups 1 and 3 (p-value = 0.032, Figure 52).

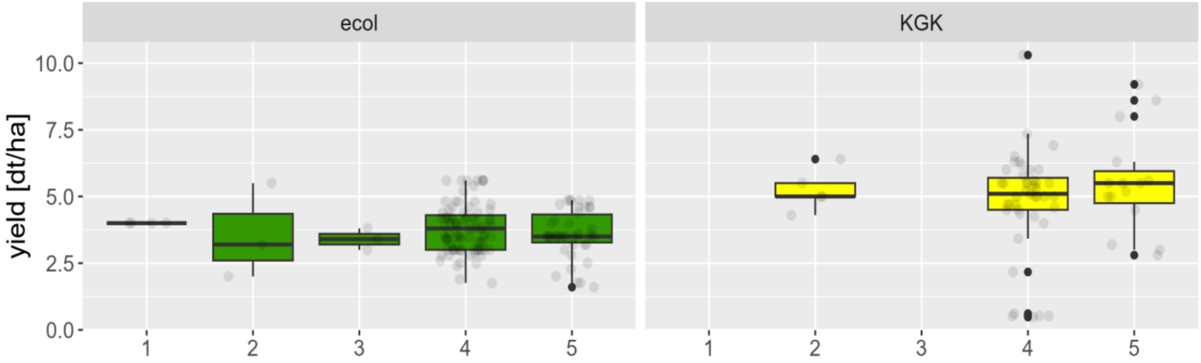

Figure 52: Influence of soil type group is almost nowhere significant. Fields with sandy soils (1) in ecological farming show higher yields than fields of soil type group 3 (adapted after LUFA (Geologischer Dienst NRW, 2019)) on yield (n_{ecol} = 135, n_{KGK} = 63)

Within the Kraichgau Korn data set, yield increases with increasing measure of productivity ("Bodenzahl") (p-value = 0.002333, adj. R^2 = 0.1205). None of the other cultivation methods shows a significant trend (organic farming (p-value = 0.3233, adj. R^2 = - 0.0001517), Linzgau Korn (p-value = 0.9505, adj. R^2 = -0.1106), Albkorn (p-value = 0.787, adj. R^2 = -0.2957), Figure 53).

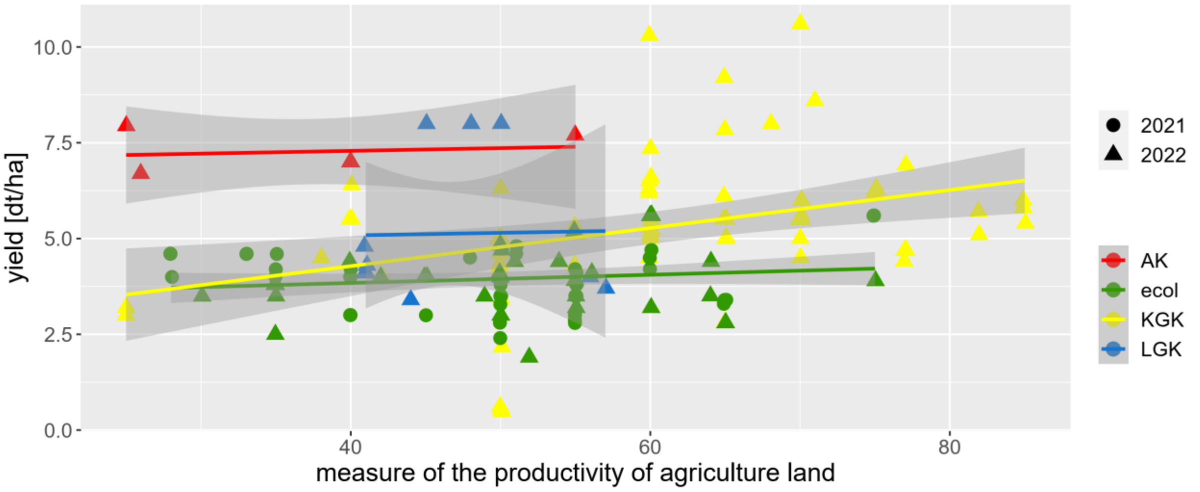

Figure 53: KGK fields yield higher with a higher measure of productivity of agricultural land, but no other farming methods show significant trends (n_{ecol} = 83, n_{KGK} = 67, n_{LGK} = 11, n_{AK} = 5), shape indicating sample year

The pH value only influences yield in Linzgau Korn (p-value = 0.01311, adj. R^2 = 0.3107), but not in Albkorn (p-value = 0.6217, adj. R^2 = -0.07979), Kraichgau Korn (p-value = 0.5386, adj. R^2 = -0.009448) and ecological farming (p-value = 0.8992, adj. R^2 = -0.01144, Figure 54).

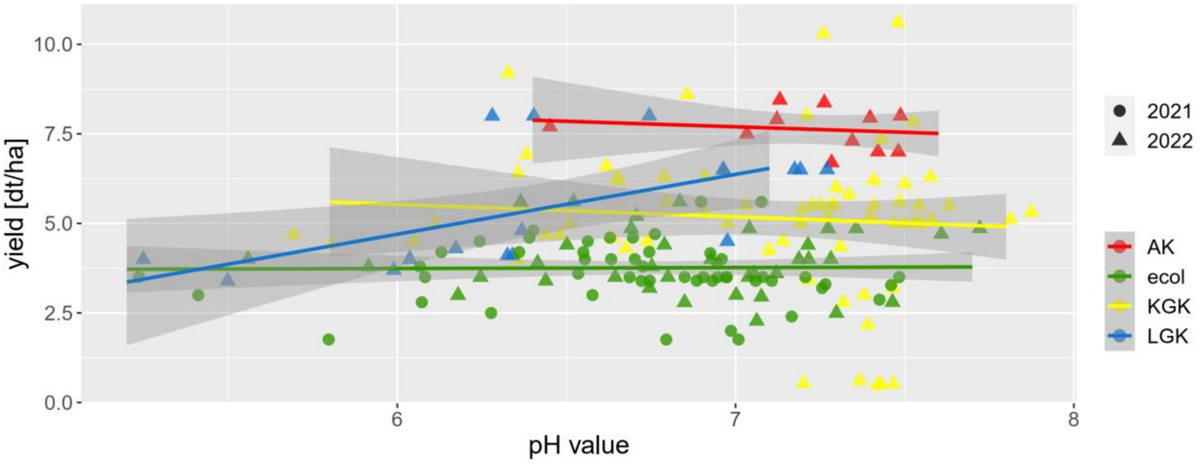

Figure 54: LGK fields with a higher pH value achieve higher yields, no other farming methods show significant trends (n_{ecol} = 161, n_{KGK} = 80, n_{LGK} = 13, n_{AK} = 11), shape indicating sample year

3.2.4 Influence of farming practices on yield

The influence of row spacing at sowing on yield in ecological farming shows a significant trend contrary to expectations: it increases with greater row spacing (Figure 55).

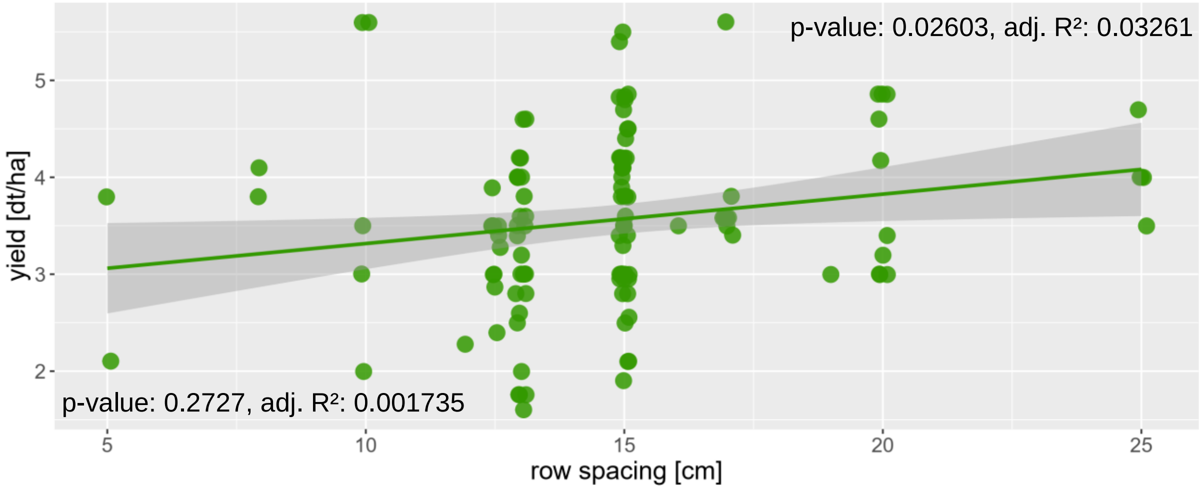

Figure 55: Yield increases with greater row spacing in organic farming (n = 122)

Yield decreases significantly at a higher seed rate in organic farming (Figure 56).

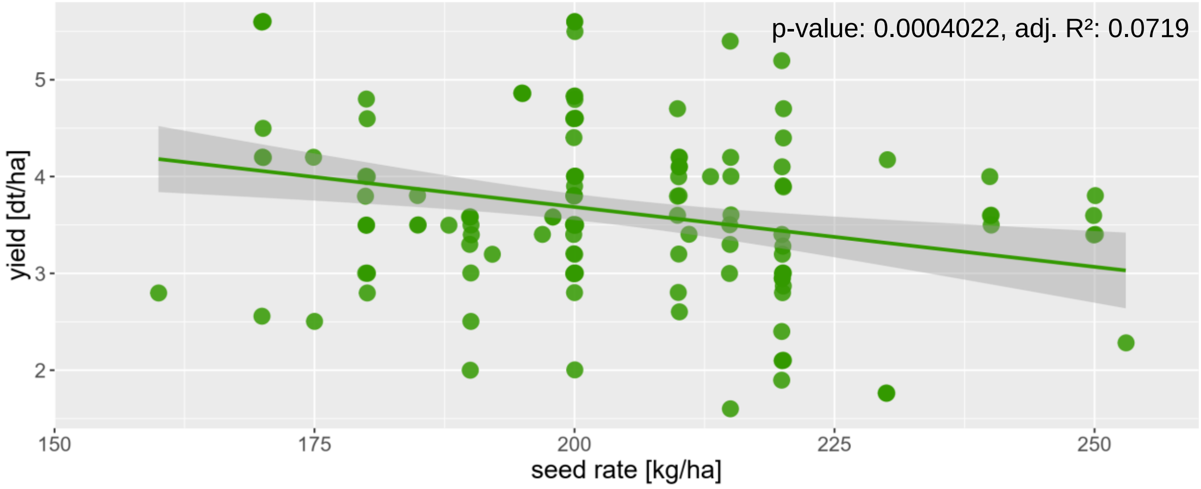

Figure 56: Yield decreases with higher seed rate in organic farming (n = 157)

The maximum depth of soil tillage as indicated by the farmers also has no significant influence on the yield in any of the studied cultivation methods (ecol: p-value = 0.05841, adj. $R^2 = 0.0162$; KGK: p-value = 0.2147, adj. $R^2 = 0.007101$; LGK: p-value = 0.2463, adj. $R^2 = 0.02769$; AK: p-value = 0.1539, adj. $R^2 = 0.1008$, Figure 57).

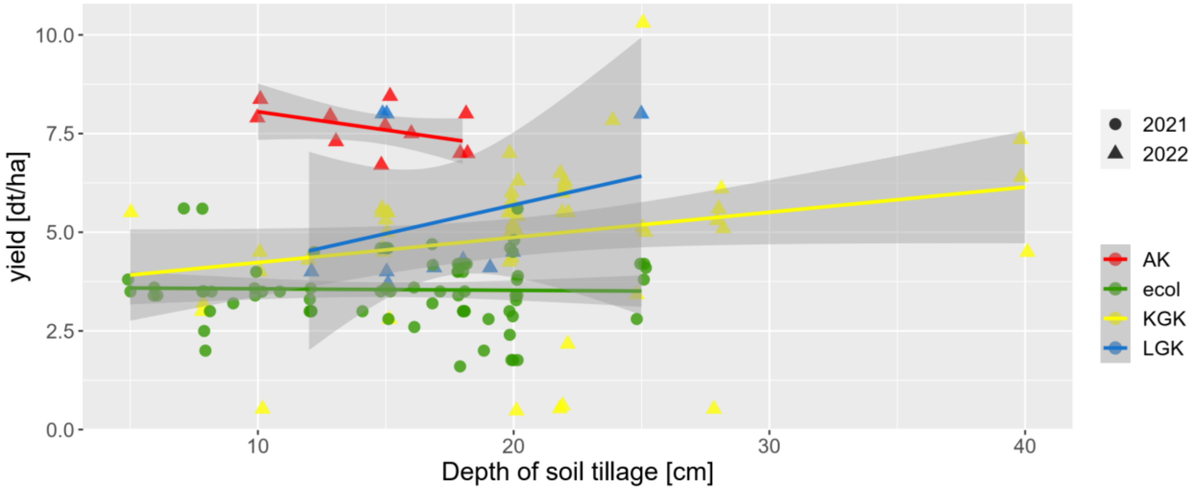

Figure 57: No significant influence of depth of soil tillage on yield was found (n_{ecol} = 81, n_{KGK} = 57, n_{LGK} = 10, n_{AK} = 11), shape indicating sample year

Yield is slightly higher in ploughed fields than in unploughed fields (Figure 58), as ecological farming shows (p-value 0.029). For KGK, the difference is not significant (p-value 0.064).

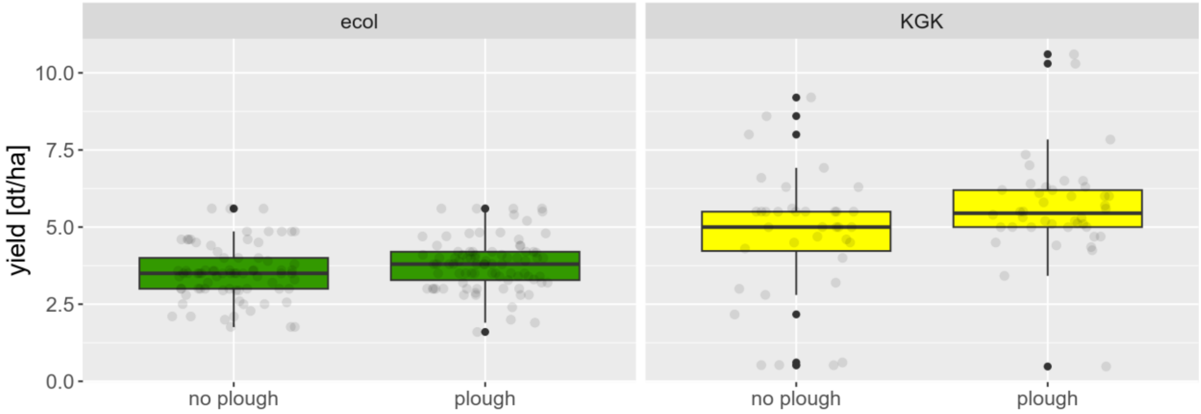

Figure 58: Yield is slightly higher in ploughed fields than in unploughed fields in ecological farming, while for KGK, there is no significant difference (n_{ecol} = 161, n_{KGK} = 78)

If we compare within the group of organic farmers those who do not work their soil and only operate according to the "sow and harvest" principle with those who use tools such as currying and hoeing to reduce the arable wild flora, it becomes clear that there is a significant difference between currying/hoeing twice and currying/hoeing less than two times. All other processes do not differ significantly from each other. The maximum yield was achieved with two currying/hoeing operations (Figure 59).

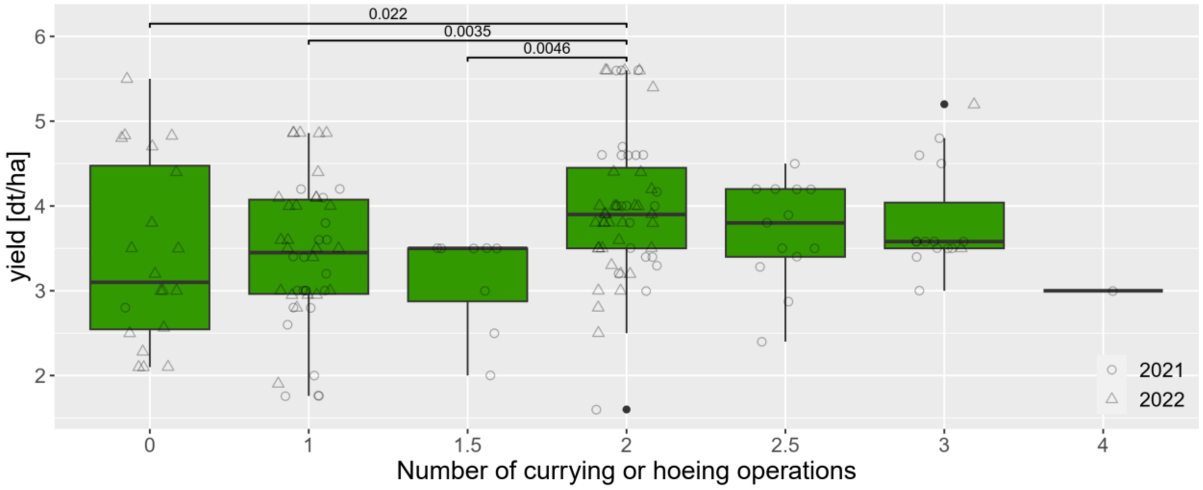

Figure 59: The number of currying and hoeing operations in ecological farming does barely have an effect on the yield, the only significant differences could be found between less than two or two runs (n = 160), shape indicating sample year

The sample of fields per variety or mixture of varieties is small, in some cases the varieties were only grown on one field each. A statistical significance test was therefore not carried out. In this study, one field with the variety "Moschus" produced the highest yield, but also the lowest (Figure 60).

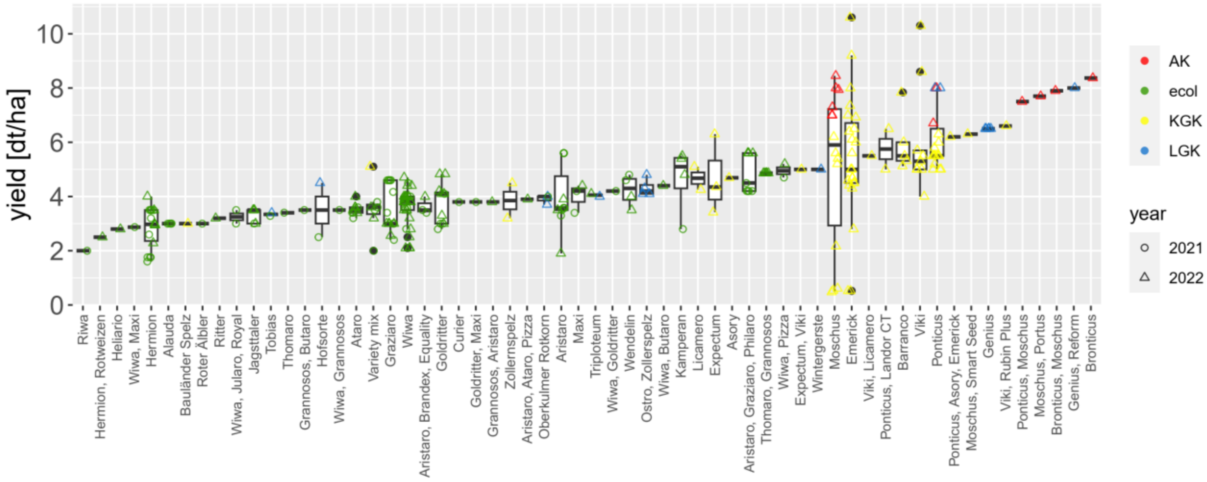

Figure 60: Yield in dt/ha per variety shows similar clustering as the comparison of farming methods, shape indicating sample year

On the basis of the organic farmers' data set, the effect of the number of crop rotation elements on yield was analysed (Figure 61). The crop rotation consisting of nine elements resulted in a significant increase in yield, while all other differences remained insignificant (p-value < 0.05).

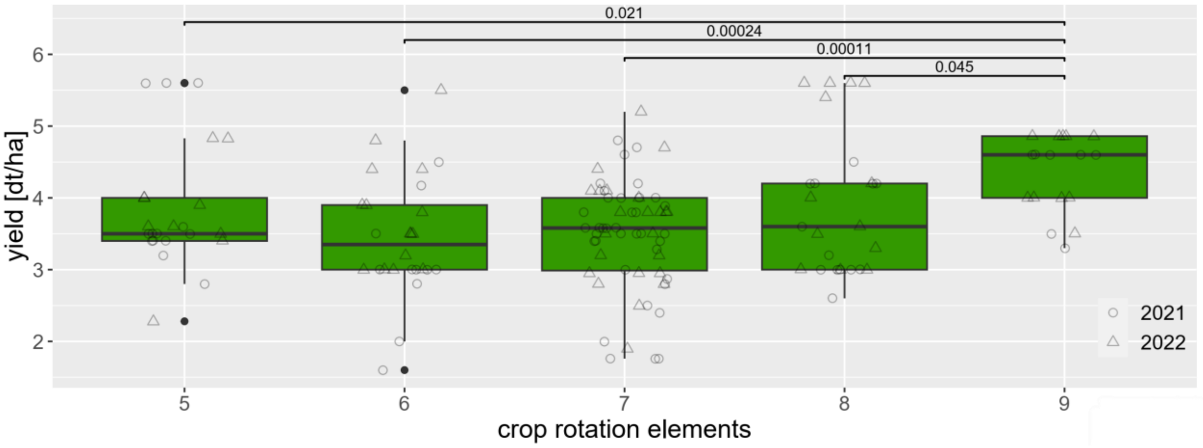

Figure 61: Yields are higher on fields with a higher number of years of the crop rotation (n = 152), shape indicating sample year

3.3 Consideration of the results at species level

For nature conservation and the preservation of arable land as a diverse habitat for other organisms, it is not only important how much grows in the fields, but above all what grows there and how frequently species that have become rare still occur. The following chapter therefore analyses the results in terms of species composition and ecological value of the individual species.

3.3.1 Categorization into plant communities

The species found in the fields could be assigned to a total of eight different plant communities (Figure 62). The most frequently represented species were Stellario-Aperetum spicae-venti („Vogelmieren-Windhalm-Gesellschaft“), 252 times in total, and Stellario mediae-Papaveretum rhoeadis („Vogelmieren-Klatschmohn-Gesellschaft“), 111 times in total. In 73 fields, the assignment to a plant community was not possible either because of a too low number of species found or because of the composition of the species.

The plant communities Apero-Lathyretum aphacae („Rankenplatterbsen-Gesellschaft“) and Papaveretum argemones („Sandmohn-Gesellschaft“) are classified in the Red List of Plant Communities (Rennwald et al., 2002) as category 2 - critically endangered, which are plant communities with formerly more frequent occurrence, which have declined very strongly in terms of stand size and number of stands in almost the entire area and have already disappeared regionally. They are endangered in most of their local distribution area. Both fields, where

Papaveretum argemones was determined, were from Kraichgau Korn, one in 2017, as was the one field of Apero-Lathyretum aphacae, and one in 2022.

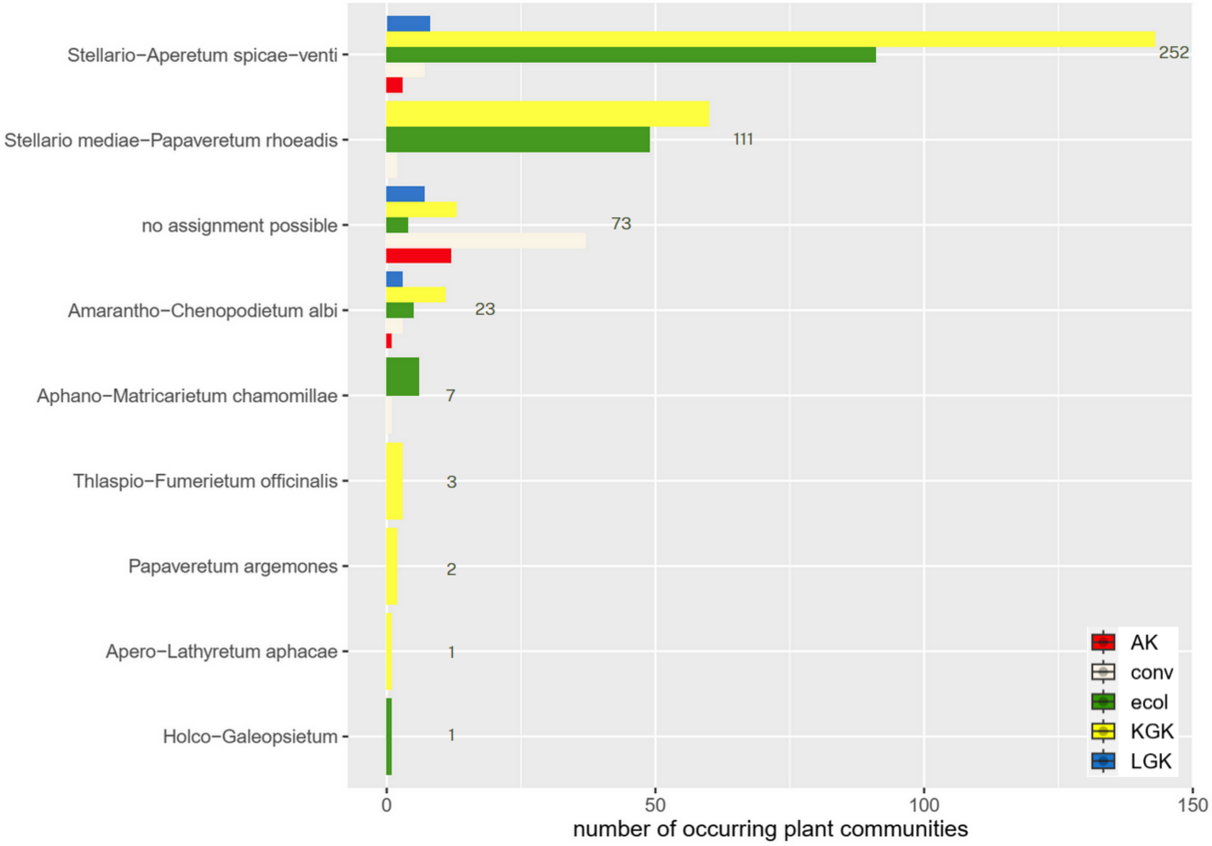

Figure 62: number of occurring plant communities per cultivation method, Apero-Lathyretum aphacae and Papaveretum argemones are critically endangered, Holco-Galeopsietum and Aphano-Matricarietum chamomillae are endangered (Rennwald et al., 2002)

The Holco-Galeopsietum (“Honiggras-Hohlzahn-Gesellschaft”) and Aphano-Matricarietum chamomillae (“Ackerfrauenmantel-Kamillen-Gesellschaft”) communities are also considered endangered and are listed in category 3: Plant communities that are clearly and steadily declining in large parts of the area, that have already disappeared locally and are endangered in large parts of their local distribution area (Rennwald et al., 2002). The community Holco-Galeopsietum was determined on an ecological field in 2022. All fields from Aphano-Matricarietum chamomillae were from 2021 and 2022, one being conventionally and six ecologically farmed.

3.3.2 Most frequent species and Ellenberg indicator values

Of the 286 different species found, 20 were cultivated plants such as bean, rapeseed or barley, leftovers from the previous year or input through wind from a neighbouring field.

When analysing the species found, it becomes clear that there are some very dominant species that were present in a large number of fields (table 3). This applies in particular to *Veronica persica*, *Galium aparine* and *Papaver rhoeas*, which were found in over 60 % of the surveyed fields. The latter is a class character species for the plant community *Stellario mediae-Papaveretum rhoeadis* identified in many fields. Four more species were found on at least half of all fields and 19 further species occurred on at least one out of five studied fields. 77 species were found only once. Of the species found, 87 can be described as archaeophytes (plants that were not originally native but were introduced before 1492), 12 are either archaeophytes or autochthonous (= native), three could be categorized as archaeophytes or neophytes. 132 are autochthonous, 18 are cultivated plants and 32 are neophytes.

Table 3: Frequency of the most common species found (> 20 % of all study sites)

species	n	% of total n
Veronica persica	324	66.94 %
Galium aparine	306	63.22 %
Papaver rhoeas	293	60.54 %
Alopecurus myosuroides	255	52.69 %
Cirsium arvense	253	52.27 %
Polygonum aviculare	251	51.86 %
Stellaria media	246	50.83 %
Tripleurospermum inodorum	239	49.38 %
Convolvulus arvensis	237	48.97 %
Chenopodium album	227	46.90 %
Fallopia convolvulus	213	44.01 %
Myosotis arvensis	212	43.80 %
Matricaria chamomilla	208	42.98 %
Apera spica-venti	182	37.60 %
Capsella bursa-pastoris	163	33.68 %
Lamium purpureum	158	32.64 %
Viola arvensis	145	29.96 %
Rumex crispus	126	26.03 %
Lapsana communis	120	24.79 %
Taraxacum officinale	119	24.59 %
Poa annua	115	23.76 %
Centaurea cyanus	114	23.55 %
Geranium dissectum	101	20.87 %
Sinapis arvensis	101	20.87 %
Trifolium pratense	100	20.66 %
Thlaspi arvense	99	20.45 %

Of the Top 100 species (Flora Naturkundemuseum, 2023) in Baden-Württemberg (list of the most frequently occurring species as of number of ¼ MTBs in which the species occur), 61 have been found within this study. This list, however, includes all species, including trees, bushes and herbs associated with other habitats, e.g. forests.

A look at the distribution of the Ellenberg indicative values reveals a relatively even Gaussian distribution of all values (see Figure 63). The majority of the species have a moisture value F of F4 and F5, so there is a wide range between dryness, freshness and moisture indicators, but with a strong peak. The continentality index K shows a clear peak at K3, oceanic to sub-oceanic species that favour high humidity, low temperature fluctuations, mild winters and temperate summers. However, some plants also show higher values here, i.e. they can cope with greater temperature fluctuations and lower humidity. The peak light value L is 7, so most plants are semi-shade to half-light, half-light or half-light to full-light plants. The most even distribution is shown by the nutrient count N, with the plants found showing very different requirements, ranging from nutrient-poor to high nutrient-indicator plants. The reaction number R peaks at R7, so most species do not occur on strongly acidic soils and tolerate lime. Only very few species are acid indicators. As the temperature value T shows, most species are moderate warmth to warmth indicators, i.e. montane to colline species.

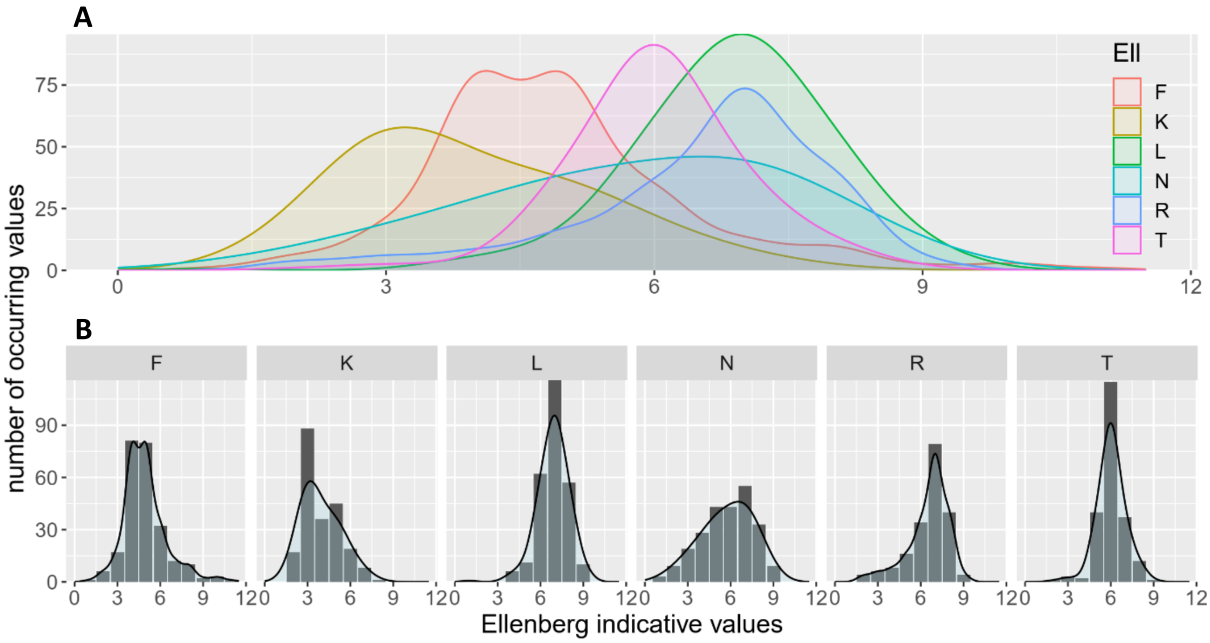

Figure 63: Gaussian distribution of all studied Ellenberg indicative values

Moreover, I calculated the average values of the Ellenberg indicator values per field and plotted them over a map of Baden-Württemberg (Figure 64). However, no clear regional distribution can be recognized for any of the values. It was tested whether the Ellenberg value "T" correlates with the average temperature values used in the data set as read out for the respective location. The correlation coefficient of 0.303 indicates a weak positive correlation between the calculated average Ellenberg value and the mean temperature according to the nearest measuring point. A linear regression yielded a p-value of 3.272e-09 with an adj. R²-value of 0.08934, indicating that the relationship between the values is significant.

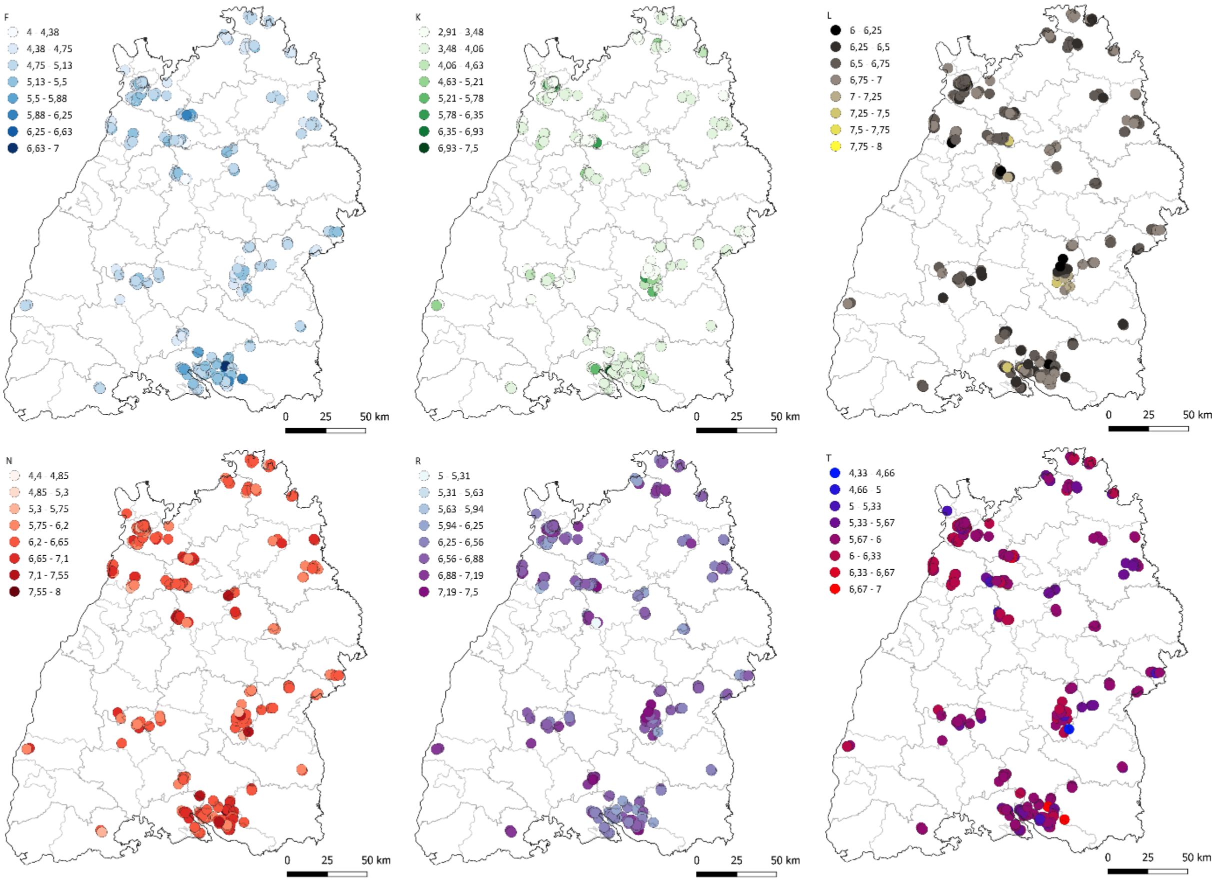

Figure 64: Distribution of mean Ellenberg indicative values per field shows no clear tendencies of regional distributions in any of the studied values

3.3.3 Red list species and (especially) valuable species

36 of the species found are on the Red List of ferns and flowering plants of Baden-Württemberg (Breunig & Demuth, 2023), including one with an unclear endangerment category ("G"), 8 on the early warning list ("V"), 12 are classified as endangered ("3"), 9 as critically endangered ("2") and 6 as threatened with extinction ("1"). A total of 36 (especially) valuable species were found in all fields, of which 18 were valuable (“w”) and 18 especially valuable (“bw”, see chapter 2.4.4). Most of the (especially) valuable species overlap with those in the red list (table 5). In total, there are 42 species with a special status, which corresponds to 15 % of the total number of species found.

Table 4 shows how many fields were found with valuable, particularly valuable or R species and Red List species and how many of the fields can be categorized in which of the categories described in chapter 2.4.4. In terms of the ecological value of the fields, organic farming shows what is possible: more than a quarter of all fields can be assigned to category 3, only a fifth of the fields to category 0. Albkorn and conventional fields show the opposite; even Linzgau Korn only achieves category 2 in exceptional cases. Kraichgau Korn shows a relatively wide dispersion, with 44 % of the fields falling into category 0, but still a fourth of all fields into category 2 and 10 % into category 3. 86 fields show valuable species, 24 fields show especially valuable species. R species were found on 61 fields, 101 fields can be considered as species rich, of which seven were mapped in 2022 and 13 in 2021.

Table 4: Number of fields (percentage of fields of the respective farming method) where (especially) valuable species, R species or Red List species were found and the field's categorization

		total (n = 482)	**Ecol (n = 164)**	**KGK (n = 234)**	**LGK (n = 18)**	**AK (n = 16)**	**Conv (n = 50)**
categorization	**cat. 0**	211 (43.8 %)	36 (22 %)	103 (44 %)	13 (72.2 %)	15 (93.8 %)	44 (88 %)
	cat. 1	83 (17.2 %)	34 (20.7 %)	42 (17.9 %)	3 (16.7 %)	0	4 (8 %)
	cat. 2	120 (24.9 %)	50 (30.5 %)	65 (27.8 %)	2 (11.1 %)	1 (6.2 %)	2 (4 %)
	cat. 3	68 (14.1 %)	44 (26.8 %)	24 (10.3 %)	0	0	0
Red List Baden-Württemberg (Breunig & Demuth, 2023)	**R1**	15 (3.1 %)	7 (4.3 %)	7 (3 %)	1 (5.6 %)	0	0
	R2	33 (6.8 %)	23 (14 %)	10 (4.3 %)	0	0	0
	R3	104 (21.6 %)	42 (25.6 %)	59 (25.2 %)	2 (11.1 %)	0	1 (2 %)
	RG	1 (0.2 %)	0	1 (0.4 %)	0	0	0
	RV	64 (13.3 %)	42 (25.6 %)	18 (7.7 %)	0	4 (25 %)	0
(esp.) valuable and R species	**w**	165 (34.2 %)	74 (45.1 %)	86 (36.8 %)	2 (11.1 %)	1 (6.2 %)	2 (4 %)
	bw	68 (14.1 %)	44 (26.8 %)	24 (10.3 %)	0	0	0
	R	136 (28.2 %)	72 (43.9 %)	61 (26.1 %)	2 (11.1 %)	0	1 (2 %)

Among the Red List species (Breunig & Demuth, 2023), *Consolida regalis* (9.30 %) achieves the highest consistency, followed by *Valerianella dentata* (8.88 %) and *Ranunculus arvensis* (5.37 %). All other Red List species detected show a consistency of less than 5 %, 12 were only found in one field each.

Table 5: Plant species with a special status (red list/(especially) valuable species, R-species)

Scientific name	*Red list status (Breunig & Demuth, 2023)*	*(esp.) valuable (Schach et al., 2023)*	*R species*	*consistency*
Adonis aestivalis	2	bw	R	0.21 %
Agrostemma githago	1			1.45 %
Aphanes arvensis		w	R	11.16 %
Bromus arvensis	3	w		0.62 %
Buglossoides arv.	3	bw	R	1.45 %
Calendula arvensis	1	bw	R	0.41 %
Camelina microcarpa	2	bw	R	0.21 %
Caucalis platycarpos	1	bw	R	0.21 %
Consolida regalis	3	w	R	9.30 %
Euphorbia exigua	V	w	R	4.34 %
Euphorbia platyphyllos	V	w		1.45 %
Fumaria parviflora	1	bw		0.21 %
Fumaria schleicheri	2			0.21 %
Fumaria vaillantii	V			2.07 %
Galium spurium	G	w	R	0.21 %
Juncus bufonius		w		0.21 %
Kickxia elatine	3	w		1.65 %
Kickxia spuria	3	w		1.65 %
Lathyrus tuberosus		w		2.89 %
Legousia sp.-veneris	2	bw	R	1.65 %
Lepidium coronopus	3			0.62 %
Myosotis discolor	3	bw	R	1.24 %
Myosurus minimus	2	bw	R	0.62 %
Neslia paniculata	2	bw	R	1.24 %
Odontites vernus	2	bw	R	2.27 %
Papaver argemone	V	w		0.21 %
Papaver dubium	V	w		1.65 %
Phelipanche ramosa	1	bw		0.21 %
Prunella vulgaris	3			0.21 %
Ranunculus arvensis	3	bw	R	5.37 %
Scleranthus annuus	V	w		0.21 %
Sherardia arvensis		w		7.64 %
Silene noctiflora	3	w		4.55 %
Stachys annua	2	bw	R	0.21 %
Valerianella dentata	V	w		8.88 %
Valerianella rimosa	2	bw		0.41 %
Veronica agrestis		w		1.45 %
Veronica opaca	1	bw		0.62 %
Veronica polita		w		4.13 %
Veronica praecox	3	bw	R	0.83 %
Veronica triphyllos	3	bw	R	0.41 %
Vicia lathyroides	V			0.21 %

The Red List (Breunig & Demuth, 2023) also contains a categorization according to nature conservation importance (NB = Naturräumliche Bedeutung). When I calculated the average values of the plants occurring in the individual fields, it resulted in a similar picture (Figure 65): Kraichgau Korn and organic fields perform significantly better than conventional fields. When plotting the sum of all NB values per field, the distribution is very similar as to looking at the Shannon Index.

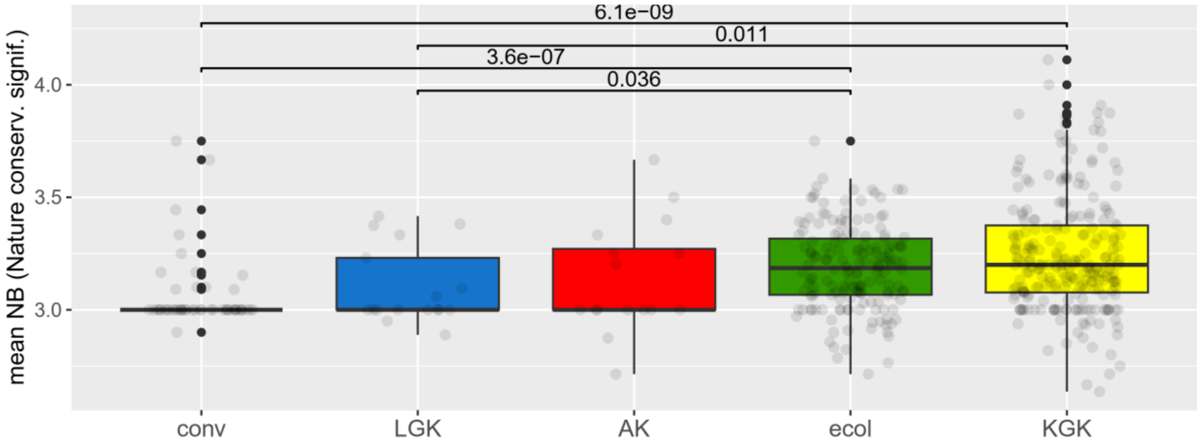

Figure 65: KGK and ecological farming have a higher mean nature conservation significance than conventional farming (n_{ecol} = 81, n_{KGK} = 57, n_{LGK} = 10, n_{AK} = 11, n_{conv} = 11)

4 Discussion

In the discussion, the results with regard to the number of species found on each investigated field and the Shannon Index calculated from this are first discussed, followed by a closer look at the yields achieved under different conditions. Furthermore, the vegetation mapping is discussed with regarding the plant sociology and biology of the individual species. I then take a closer look at the problems that a widespread conversion to organic farming could cause and what options there are to circumvent them. I discuss the availability and difficulties of organic varieties. Finally, I consider further ideas and options for protecting or promoting biodiversity in the agricultural landscape.

4.1 Classification of the results

Biodiversity on the studied fields

The number of species found on each crop field and therefore the Shannon Index depends on many different factors, especially on pesticide use. It is not surprising that biodiversity on organic fields is significantly higher than on fields treated with chemical pesticides and verifies my hypothesis. The fact that Kraichgau Korn achieves such significantly higher values than other farming communities is probably partly due to the fact that it is not sprayed in the growing year. However, the Kraichgau has a mild climate, fertile soils and in some cases a high lime content, making it generally favourable for the development of a rich weed flora. In addition to the naturally very species-rich loess landscapes in the Kraichgau, the inclusion of mapping from the years 2016-2019 further reinforces the effect, which can also be explained by the specific selection of particularly species-rich fields for participation in the field weed championship, from which the data originates.

The high dispersion of values within the Linzgau Korn data set can be explained by the fact that organic and conventional farmers cultivate together in this farming community. If the Linzgau Korn data set were larger, it would be ideal for analysing the differences between conventional and organic cultivation without environmental conditions playing a major role, as the cultivation region is relatively small. The small sample size of the Linzgau Korn, Albkorn and conventional fields is particularly striking when investigating the environmental influences on the Shannon Index. A significant trend is hardly recognizable here, but at most suggests a tendency. The fact that the Shannon Index increases with more precipitation and decreases with higher temperatures emphasizes the concern about further impoverishment of the landscape with increasing climate change. Global warming will also increase the likelihood of seed germination either during the winter season or after dispersal, which influences plant reproduction success (Bernareggi et al., 2016). Even if seedlings can survive through winter, it may reduce their growing capacities in spring. Although the results regarding frost events were inconsistent in my study, it therefore is presumable that species that depend on frost to break seed dormancy will continue to decline and eventually become extinct as a result of climate change. These cold germinators include for example the endangered *Adonis flammea* (Kolodziejek, 2018).

Soil plays a fundamental role in agriculture due to its various contributions to plant growth and ecosystem health. Depending on the physical and chemical properties, soil can affect the growth of crops and arable weeds largely (Parikh & James, 2012). For example, sandy soils provide good drainage, but clay soils have higher water retention and are generally richer in nutrients. In my study, fields with sandy soils showed significantly higher Shannon Indices. The composition of the soil influences water movement, circulation of air and nutrients (Yang et al., 2022). Its pH value can have a significant impact on crop growth as it influences the availability of nutrients: in acidic soils, elements like phosphorus and magnesium are less available for plants. Suboptimal pH levels can affect the activity of soil organisms, inhibit the survival of beneficial bacteria and restrict root development, which again affects access to water and nutrients (Gentili et al., 2018). As no soil samples were taken in the course of the investigations, it was necessary to rely on the information obtained from the farmers, which was only incompletely provided. No influence can be recognized with regard to the diversity of arable flora. This also applies to the soil number.

Managing for soil health is vital for reducing erosion, maximizing water infiltration, improving nutrient cycling, and ultimately enhancing the resiliency of agricultural land. Farmers have a particularly direct influence on arable weeds through the methods they use to cultivate their fields and manage their soil. When sowing, the row spacing and seed rate determine how much space remains between the plants later on. A wider row spacing makes it easier to harrow the field, for example. However, neither row spacing nor seed rate have a significant influence on the Shannon Index. With regard to the influence of the number of currying or hoeing operations, I would have expected a clearer trend of a declining Shannon Index with more operations, as they are primarily carried out to reduce the associated weed flora. One possible explanation is that harrowing prevents dominant species from overgrowing, which in turn allows less competitive species to survive (Adeux et al., 2019, Benvenuti & Bretzel, 2017). The effects of the depth of tillage show no significant results for any cultivation method with regard to diversity in the fields.

In the case of organic fields, ploughing has a negative effect on the arable weeds, but Kraichgau Korn shows the opposite. When turning the soil with the plough, plant residues are worked into the soil so that they decompose quickly. In this way, pests are also brought into deeper soil layers, which they usually cannot survive. Ploughing loosens the soil and aerates it, which leads to faster warming and drying and mobilizes nutrients. However, it also destroys the aggregate and capillary structure of the soil and decimates earthworms. The plough leaves the soil completely uncovered, exposed to the elements and therefore highly susceptible to silting and erosion. All these factors can lead to reduced soil bearing capacity and compaction in the long term. By ploughing, the plant residues are broken down more quickly and released into the atmosphere as CO_2. The no-till method would therefore save CO_2, because the carbon content accumulates in the upper soil layer due to the high proportion of organic matter. The UNEP (United Nations Environment Programme) report mentions possible savings of up to 89 % by switching to no-till farming. However, other calculations have shown that although the carbon stock near the surface increases, the content in deeper layers decreases and the accumulation of carbon stagnates over the years. Denitrification due to the more frequent waterlogging caused by compaction would occur, whereby nitrous oxide NO_2 would also be released, which is a greenhouse gas 298 times more potent than CO_2 (Powlson et al., 2014). With reduced tillage, the soil is worked much less intensively, if at all, before sowing. It provides an important contribution to soil fertility. Refraining from deep and intensive loosening protects soil structure and soil life and prevents humus decomposition. The carrying capacity, erosion control and water balance of the soil are improved and the unploughed fields do not heat up as quickly as dark, ploughed fields. However, not using the plough also brings certain challenges. Crop residues cannot be easily incorporated into the soil, which is particularly problematic after grain maize, where it can clog seed drills and harrows. Especially root weeds and light germinators benefit from reduced tillage, weed pressure can increase. Slower soil warming in spring, slower drying of moist soil, later nutrient mineralization and slower emergence of the crops are further challenges that need to be addressed when changing from ploughing to reduced tillage. Other disadvantages are compaction and poorer aeration of the soil (Powlson et al., 2014). Albrecht et al. (2016) introduced the no-till method to study the relationship between crop yields and densities of non-crop plants. Over the first five years of the study, species diversity significantly increased. But because of a strong increase in weed density, they had to apply herbicides, which resulted in a species diversity lower than under tillage. Tørresen and Skuterud (2002) found that ploughing increased the establishment of winter annuals and perennials, but decreased specialized spring annuals.

Statements about which field crop is most favourable for the arable flora could not be made. As we concentrated on winter wheat, the samples of the fields with other crops are not large enough to make statistically significant statements. The same applies to the cultivated varieties. The number of years in the crop rotation also did not show any significant differences in their influence on biodiversity in my study. Although I made every effort to minimize the influence of the study design and to keep the methodology consistent, some issues cannot be avoided. The time in which the vegetation surveys were carried out was limited as far as possible, since early bloomers can no longer be found in later surveys and the Shannon Index decreases with an increasing height of the ears, probably due to the shading they cause. With a larger sample size and especially with a longer study period over several years, it would be possible to reduce the uncertainties and get a more accurate impression of what the arable weed flora benefits from and to what extent. Furthermore, it would have been possible to reduce the influences of temperature, the course of the year and the vegetation period by limiting the time frame in which the mapping was carried out to a few days. Mapping by only a few, identically trained people, preferably with multiple mappings per field on a rotating basis, would also reduce the external influences of the study design, the prior knowledge of the mappers and the accuracy of the individual mapping. In addition, the height of the crop at the time of mapping would have less influence if each field was mapped more than once. A study by Vittoz and Guisan (2007) that tested the reliability of the monitoring of vegetation plots by multiple observers found that only 45 – 63 % of all occurring species were seen by all observers. However, the majority of the overlooked species had a cover of less than 0.1 %. Two observers overlooked up to 20 % less species than single observers (Vittoz & Guisan, 2007). It was tested statistically, whether these findings are also applicable to our study, but I found that there was no significant difference between single and multiple inspections of fields in 2021. This made it possible to focus exclusively on single mapping passes in 2022 and thus cover more fields with the same number of people. It was attempted to distribute the mappers amongst the cultivation methods, but some volunteers only examined very few fields. For logistical reasons, these mappers therefore only visited fields that were as geographically close to each other as possible, which were then usually farmed by the same farmer. The difference in the results could therefore be explained by the farming method of this specific farm, which explains the partly large differences between some of the mappers. The resulting small sample sizes do not permit statistical analyses to examine the differences between the individual mappers. But by asking about previous experience and adopting as uniform an approach as possible, differences in the level of knowledge and methodology were minimized as far as possible. Furthermore, the error rate was reduced to a minimum by taking photos and herbarium specimens, which Dr. Peter Sack and I verified. Finally, I decided where the transects should be positioned in the field. Previous studies showed clear differences between the diversity at the edge of the field, where more arable flora could be found, influenced by flower strips or benefiting from less shade from the field crop, than in the centre of the field (Schraml, 2018, 2019). For example, in the reports on the field weed championship, the numbers of species were significantly higher in the headland than in the centre of the field for all crops across all years of the study. The headland is not representative of the entire field, but since we wanted to avoid trampling down more than necessary, the transect was defined as it was ultimately carried out: sufficiently far away from the edge of the field to minimize influences from outside, but no further into the centre than required. In order to still be able to discuss whether this was the right decision, a subset of the fields was also investigated towards the centre of the field, which resulted in a slightly lower species diversity. But the large number of study areas, the limited time available, the personnel required and the sometimes long travelling distances between the individual fields did not allow any further improvements in the study design, as it would have taken way more time.

The impact on yields

The fields examined in my study show that organic farming achieves significantly lower yields than Kraichgau Korn and Linzgau Korn. Albkorn again achieves significantly higher yields than the other three groups. These findings are overall consistent with the results of other studies, as discussed in the introduction. In all comparisons between Kraichgau Korn and organic farming, it is important to remember that the Kraichgau region has one of the best agricultural soils in Baden-Württemberg. While the state average of the average adjusted yield measurement figures (dbEMZ) is 44.6, the Kraichgau region almost universally achieves yield measurement values of > 60 (Infodienst Landwirtschaft, 2024). The EMZ hereby is an index for the natural yield capacity, determined based on the natural yield conditions (EMZ = Acreage number x area/100). It is required for the property tax declaration and corresponds to the definition in § 9 of the Bodenschätzungsgesetz (Soil Appraisal Act).

Organic farming shows a significant decrease in yield as the Shannon Index increases: the more species-rich the field, the lower the yield. This reflects the trade-offs between biodiversity and agricultural productivity due to competition for resources, utilization efficiency or management challenges as discussed before. Although the robustness of organic varieties against yield fluctuations is often advertised, this does not apply to greater tolerance to weeds. Instead, a higher shading capacity has been shown to significantly reduce the shoot growth of weeds (Drews et al., 2009).

I then studied the environmental influences on yield. The height above sea level of the fields seems to have a negative influence on ecological fields, but a positive one on those of KGK. However, no Kraichgau Korn field is situated higher than 500 m above sea level, but most of the organic fields are. Yield decreases with more rain, which seems unusual at first, given the prevailing dry periods due to climate change. One possible explanation is an unfavourable distribution of rain events, especially the occurrence of heavy rainfall. The previously dried out soil can hardly absorb any water and therefore does not benefit from the rainfalls (Márton et al., 2007). Temperature, on the other hand, seems to have little influence, as only the average temperature in organic farming has a significant effect on yield. In addition, in the case of Kraichau Korn, the occurrence of a frost event resulted in increased yield. Lobell and Field (2007) found, that at least 30 % of variations in average yields can be explained by spatial averages of precipitation and air temperatures based on the crop's locations. They report a clearly negative response of global winter wheat yields to increased temperatures. The climate-related losses in yield have so far been offset by technological yield gains over the same period. But growth of yields has stagnated over the past 30 years, an indication that the effects of climatic variability have increased significantly.

The soil number does not have a significant influence on organic fields, which can be explained by higher resilience of the used organic varieties against external factors. They are also capable of producing stable yields in lower-yielding areas. Kraichgau Korn showed a significant correlation between increasing soil number and increasing yield, which is not surprising since the soil number quantifies the fertility of the soil. But in the case of another analysed factor, the yield runs contrary to expectations: fields with greater row spacing show higher yields, although there are correspondingly fewer ears on the same area. The more was sown, the less could be harvested. In many studies (e.g. Fischer et al., 2019; Lafond, 1994), wide rows do not only offer arable weed plants a good potential for spreading and increase the number of kernels produced per ear. The wider row spacing enables more even rooting. The wheat plant is under less stress at lower seed densities and experiences less intraspecific competition. High seed densities cause uneven, narrow spacing between the plants, while reduced row spacing can increase canopy coverage and reduce soil evaporation (Chen et al., 2010). Therefore, wider row spacing and lower seed density can have a positive effect on yield (Iqbal et al., 2010).

The number of currying or hoeing operations shows significant differences in whether the field is not worked at all, once or twice. More than twice again makes no difference, which is confirmed by a farmer in a conversation who says that too much harrowing causes stress in the crop, which in turn reduces yields. This is underlined by the results of other studies, where frequent harrowing had no positive effect on yield (Benvenuti & Bretzel, 2017; Navntoft et al., 2016). As in the case of species diversity, a further discussion of the influence of cultivated crop and variety is not expedient due to the small sample size. The population varieties and variety mixes are in the midfield in terms of yield and show no clear differences to other organic varieties, either in a positive or negative sense. A crop rotation consisting of many elements has a positive effect on yield, as shown in my results. Crop rotation is not only a way to mitigate pathogen, weed and insect pressure, it also restores plant nutrients, requiring less chemical fertilizer. It has long been known that this also increases yields and reduces trade-offs between crop viability and environmental impacts (Li et al., 2019). In a study by Zhao et al. (2020), rotation increased crop yields by 20 % on average, and Volsi et al. (2021) found that diversified systems presented higher profits even despite higher cost.

4.2 Can organic farming or transitional models save the planet?

Is organic farming a solution to climate change? Can Kraichgau Korn, Linzgau Korn and Albkorn serve as transitional models for organic farming?

Weather conditions are changing worldwide: heavy rainfall events and periods of drought are forecast to increase in the coming decades, which will also be accompanied by a decrease in the water available in the water balance for the summer months (Brasseur et al., 2017). They also increase the vulnerability of the soil to the erosion of the nutrient-rich topsoil, which in turn reduces the carbon storage capacity. Some regions, such as Oberrheingraben and Kraichgau, are particularly affected by this due to their geographical location. Furthermore, living conditions in some areas are shifting at a speed that exceeds the dispersal rate of many species (Chen et al., 2011). Their poor adaptation to their rapidly changing environment makes species and ecosystems more susceptible to pathogens (Brasseur et al., 2017). Greater resistance could be achieved through enhanced biodiversity as genetic variability enables better adaptation (Assmann et al., 2014).

The results of my investigations show that organic farming has by far the greatest potential for species-rich agricultural landscapes. Endangered species also benefit from the temporary avoidance of pesticides, as in the case of Kraichgau Korn, albeit to a lesser extent. All Red List species found in Linzgau Korn in all years were found in the organic fields of the farming community. The plant communities were described as mostly only heavily degraded with highly competitive problem species on the conventional fields in the report on the field weed championship, while the organic fields were reported as very species-rich with some rare species (2018: *Consolida regalis*, 2019: *Legousia speculum-veneris* and *Anthemis arvensis*, among others) (Schraml, 2018, 2019). Only three of the endangered species received a consistency higher than 5 %, while there are a few agricultural problem weeds such as *Galium aparine* (63.22 %), *Alopecurus myosuroides* (60.54 %), *Cirsium arvense* (52.27 %) and *Fallopia convolvulus* (44.01 %). However, there were also some that are important for biodiversity, such as *Papaver rhoeas* (60.54 %) or *Myosotis arvensis* (43.80 %).

Not only in my study are the numbers of endangered species alarming: The federal and state governments have been monitoring agricultural land throughout Germany since 2009. The HNV Farmland Indicator, where HNV stands for High Nature Value, is part of the framework of the EU's common agricultural policy and assesses various types of biotopes in the agricultural landscape, including arable land, in terms of their nature value. While the proportion of HNV areas in respect of arable land was 1.7 % in 2009, it was steadily decreasing until only 0.9 % in 2022 (Bundesamt für Naturschutz, 2022). A number of studies in Germany and Austria found higher numbers of endangered species in organic than in conventional fields (Fried et al., 2009; Plakolm, 1994; Van Elsen & Hotze, 2008), as well as an increased species richness in the soil seed bank (Squire et al., 2000). Those studies focused on general species richness, but e.g. Walker et al. (2007) showed that the occurrence of rare species shows similar patterns.

The avoidance of the use of pesticides, chemical fertilizers and growth regulators on some fields and the rotation between the use of the fields contribute to a lower input of not only pesticides but also nitrate into the groundwater. There is less nitrate introduction in the soil and less acidification than in regular conventional agriculture. The significantly higher values for species number and diversity in Kraichgau Korn and the heaped endangered species on these fields show that a renunciation of pesticides in certain years can have a great effect on biodiversity. By leading to a greater diversity in the arable flora we can suggest an effect on the diversity of insects and soil organisms, that could already lead to significantly more resistant and stable ecosystems (Koch et al., 2023). Transition models could make it easier for farmers to shift from conventional to more sustainable agriculture and to organic farming. Cooperation between farms and the experience that individual farmers have gained over the years can make the transition easier for new entrants. Potential crop failures of individual farmers are compensated by the joint economic income, which provides additional financial stability. By gradually adopting practices that are common in organic farming, the likelihood of a complete switch to organic farming increases (Koch et al., 2023). An example in Switzerland shows that this concept works on larger scales: under the IP-SUISSE label, around 18,500 farmers produce under public-private production standards pesticide-free wheat within its so called “Extenso” program (Möhring & Finger, 2022).

Financial aspects of the transformation

A small parcellated structure of the landscape with many varying elements is ideal for a high level of biodiversity (Sánchez et al., 2022). However, an increase in farm sizes in Germany over time counteracts this (Statistisches Landesamt Baden-Württemberg, 2021). While the average agricultural area in 1971 was still 7.1 ha, in 2021 it was already 36.5 ha on average, with a few farms cultivating an area of more than 1000 ha. The number of farms steadily declined in the past years (3 - 5 % about 20 years ago, -0.7 % in 2020). In 2020, the percentage of full-time farms in the agricultural sector was 31 % (53 ha farm size) and accounted for the largest share of the total agricultural land in Baden-Württemberg (54.5 %). In comparison, the 56.5 % of farms operating on a part-time basis (19 ha on average) accounted for 29.7 % of the agricultural land in Baden-Württemberg. Farm size and number are considered important for a wide range of social and environmental factors, including biodiversity, yields and concentration of power in food systems. Nevertheless, models predict further declines in farm numbers by the end of the 21st century, with a doubling average farm size (Mehrabi, 2023). This will make the necessary changes even more difficult in the future. A study by Joormann and Schmidt (2017) provides an insight into the barriers and perspectives for more biodiversity in the agricultural landscape. The results show that one of the main concerns of farmers is the profitability of their farm. Transitioning from conventional to ecological farming often requires initial investment in infrastructure, equipment, and organic certification. Farmers may need to invest in new machinery, organic seeds and infrastructure for organic practices such as crop rotation and organic pest management. During the transition phase from conventional to organic farming, farmers may experience reduced yields and income due to changes in practices and the time it takes for soil fertility to improve. This transition period typically lasts several years, during which farmers may face financial challenges. A financial incentive such as premiums for biodiversity and a long-term guarantee of payments are considered important by over 70 % of participants (Joormann & Schmidt, 2017). For this reason, it is important that political and financial incentives are created for the transition to more sustainable agriculture with integrated biodiversity measures. Initiatives and market communities such as the ones analysed in our study facilitate this transition to more sustainable agriculture, as they practice an intermediate form between organic and conventional farming. The conversion costs for the individual farm are lower with these transition models than with a complete switch to organic farming. In addition, the market community provides financial security for individual farmers and they can draw on the experience and expertise of other members.

Accessing organic markets and securing premium prices may require additional marketing efforts, branding, and distribution networks, which can involve initial investment and ongoing operational costs. This is another aspect in which the market communities can provide support and draw on existing processes. Over time, ecological farming practices such as organic fertilization, crop rotation and natural pest control can lead to reduced dependency on synthetic inputs such as chemical fertilizers and pesticides, which results in further cost savings for farmers.

However, UBA (2022) presumes that the costs that farms have to bear during and after conversion to organic farming would appear less high if the environmental costs were considered. They claim that this has not been done sufficiently so far, thus there are hardly any economic incentives for farmers to reduce their environmental impact. This also inhibits the development and market introduction of environmentally friendly technologies, so that taking environmental costs into account would lead to more sustainable production and consumption patterns (UBA, 2022). This would include damage costs from nitrogen emissions, carbon dioxide and other greenhouse gases (Matthey & Bünger, 2020). As nitrogen input is another of the major global problems on which agriculture has a great influence, there are many policies dedicated to reducing agricultural nitrogen pollution. But most of them focus on changing farmer’s behaviour, although they are just one of several actors in the agricultural food-chain. Therefore, Kanter et al. (2020) suggest to not only concentrate on the farm-level but beyond: fertilizer manufacturers, traders and processors, retailers, consumers and waste water management need to be regulated, too, to address this problem in full. They are not the first to come up with this idea: Pavan Sukhdev, president of WWF (World Wide Fund for Nature) and former manager at Deutsche Bank, is convinced that nature conservation will only become interesting for the economy when every species has a price and every violation of nature has its penalty. Only when the destruction of the environment becomes so expensive that profit-making is no longer conceivable without environmental protection will the transformation to a sustainable world be possible (Ring et al., 2010).

Sustainable intensification to counter global food undersupply

Sustainability cannot be reached by solely promoting biodiversity. According to Diepenbrock et al. (2016), the requirements for a sustainable agriculture of the future consist of three parts: economy, ecology and social issues. A key aspect is the conservation of resources including natural ecosystems and biodiversity. But they also focus on ethical aspects of intra- and intergenerational justice, which demands equal opportunities for current and future generations. Noell (2002) sees agriculture as sufficiently highly sustainable even in intensive use, as there is a lack of knowledge with regard to which sustainability strategies are the most effective from an economic point of view. He states, that both organic and integrated farming have advantages and disadvantages, and that we lack quantifiable indicators. We therefore should combine the advantages of both principles in order to achieve high sustainability.

In 2022, the Russian invasion of Ukraine has shown how quickly unforeseen events can affect the global market. Particularly European countries were heavily reliant on Ukrainian wheat imports for both human consumption and animal feed, as Ukraine is the world’s fifth largest exporter of wheat (Devadoss & Ridley, 2024). Consequently, the disruptions in Ukrainian wheat exports have led to concerns about shortages and increased prices in European markets. In response, alternative suppliers had to be found and efforts to support domestic wheat production to enhance self-sufficiency were made. The war has shown the vulnerability of the global crop markets to geopolitical conflicts and has underscored the need of resilience and sustainability in agricultural production. Júnior et al. (2022) calculate, that the top export countries need to increase wheat yields or cropping areas by 8 % to compensate the Ukrainian wheat losses, but climate induced crop failures are expected to reduce export by further 5-7 million tons. This is only one example how arable land is limited. As it is expected to decline worldwide, especially due to climate induced crop failures, the concept of agricultural intensification is being applied with increasing frequency (FAO, 2019). In order to counter the known problems caused by fertilizers, pesticides and high water requirement, the term sustainable intensification was introduced: it consists of a wide range of methods such as climate-resilient and high-yielding crop varieties, intercropping, biodiversification and integrated pest management (Shrestha et al., 2021). In the face of climate change, according to Macholdt and Honermeier (2017) it is even more important to achieve more stable yields with fewer fluctuations than high yields.

An attempt to obtain climate-resilient varieties that also promote biodiversity are eco-varieties. As the varieties used in organic farming must produce consistent yields without the use of pesticides or chemical fertilizers, they are also more resistant than conventional varieties. The opportunities offered by breeding and growing organic varieties are reflected in the results of a survey of companies in the German seed market (Meysen, 2022). At least 50 % of the companies working with organic varieties saw advantages in the areas of nutrient efficiency, yield stability, weed suppression and water utilization efficiency. Advantages in resistance breeding and for the biodiversity of the crop and the ecosystem were also cited as reasons by some companies (Meysen, 2022). These results are supported by LIVESEED's report on the importance of encouraging and discouraging factors regarding the integration of organic seeds into farmers' production. The report shows that, from the point of view of the farmers surveyed, organic seed has at least no recognizable disadvantages in terms of germination and susceptibility to disease compared to conventional seed (LIVESEED, 2009).

One of the challenges for organic farming is the availability of organic seeds. Almost half of the participants in the LIVESEED report stated that organic seed is not readily available for the type of crop they grow (LIVESEED, 2019). They identified the main challenges for promoting the use of organic seed as improving the availability of locally adapted varieties and the greater effort involved in organic seed breeding (LIVESEED, 2019). The report also shows clear correlations between the geographical region in Europe and the availability and use of organic seed, as well as between the direct customers of the farmers' seed and the seed grown. The availability of organic seed is rated significantly better in Northern and Central Europe than in Southern and Eastern Europe. The use of organic seed also reflects these geographical differences (LIVESEED, 2019). The direct customer is also decisive for the type of seed grown by the farmers. The report shows that farmers who sell their products directly to organic shops or consumers tend to use organic seeds more often than those who sell their seeds through other channels (LIVESEED, 2019). This suggests that regionally operating companies in particular have a higher tendency to work with organic seed. However, this assumption was not confirmed by the survey results. The results of the LIVESEED report show that one of the major challenges in the transition to more sustainable agriculture is to involve larger seed companies in the changeover. The necessary incentives or restrictions will probably have to be set at EU policy level.

The problem of missing labelling of organically cultivated organic seeds

While statistics on the acreage, propagation areas and yields of conventionally and organically cultivated fields are freely available, there is no distinction between organic varieties of the three choices as defined in the introduction. Therefore, there is no data on the acreage of organically cultivated fields with organic varieties, resulting in missing information for 15,500 ha of winter wheat grown in Baden-Württemberg (Statistisches Landesamt, 2021). To counter this problem, an attempt of estimating was made by Cornelia Wiethaler in the scope of our project using three approaches:

1. The propagation area of organic winter wheat

Seed is produced on areas controlled by the Federal Plant Variety Office (BSA, 2021). These totalled 41,924.96 ha for common winter wheat in Germany in 2022, of which 1,889.30 ha were produced under organic conditions. This corresponds to a proportion of 4.51 %, but giving information on organic farming is voluntary, makes no claim to completeness, is not checked for accuracy and includes organic varieties, organic seed and conventional, untreated seed. The propagation area for common winter wheat in Baden-Württemberg reported to the Agricultural Technology Centre (LTZ) in 2023 was 2,082.24 ha, of which 1,848.61 ha was conventionally farmed and 233.63 ha was organically farmed (LTZ, 2023). This proportion of 11.2 % is significantly higher than the proportion of 4.51 % stated by the BSA (2021). In addition, only seven organic varieties were propagated on the statistically recorded 160 ha (Aristaro, Ataro, Castado, Grannosos, Graziaro, Pizza, Wiwa), while 28 organic varieties were used in our study, some of which must have been propagated on areas that were not statistically recorded. The 160 ha for seven organic variety propagations correspond to 68.48 % of the organic propagation area in Baden-Württemberg. Transferred to 15,500 ha of organic winter wheat cultivation area in Baden-Württemberg, this allows an estimated coverage of organic winter wheat varieties of around 10,615 ha.

2. The quantity of organic winter wheat seed sold

The BSA (2021) reports a recognized seed quantity of 261,267.52 t of common winter wheat in Germany for 2021. Of the varieties included in this amount, 19 are clearly identifiable as organic varieties with a summed up recognized seed quantity of 1,572.99 t (0.6 %) (table 6). With an average sowing quantity of 200 kg/ha, the seed quantity of these 19 organic winter wheat varieties would result in a cultivated area of approx. 7,864.95 ha throughout Germany, which is significantly lower than the acreage of 10,615 ha calculated in the first approach from the propagation areas in Baden-Württemberg alone. The total seed volume for winter wheat in Baden-Württemberg in 2022 was 13,015.35 t. Due to the fact that the seed quantities of organic varieties are lacking here as well, Bernd Habeck, Bioland trading company, was interviewed: "At the Bioland trading company, the annual share of Z seed sold for quality wheat from organic plant breeding is over 70 %." This value is much closer to the 68.48 % calculated above than the 0.6 % calculated from the BSA data and would correspond to an area of 10,850 ha for organic winter wheat in Baden-Württemberg at a sowing rate of 200 kg/ha.

Table 6: Recognized seed quantity of organic winter wheat varieties (BSA, 2021)

Organic varieties 2021	quantity [t]
Trebelir	214.25
Aristaro	202.41
Butaro	180.18
Thomaro	102.50
Roderik	95.00
Curier	59.10
Graziaro	43.70
Govelino	27.90
Tilliko	18.00
Sarastro	6.50
Grannosos	2.40
Philaro	14.50
Jularo	9.00
Fritop	5.40
Wiwa	499.52
Royal	60.00
Pizza	16.00
Wital	10.00
Ataro	6.63
organic varieties 2021 (sum)	**1,572.99**
Total seed quantity organic + conventional 2021	261,267.52

3. The reproduction rate of organic winter wheat

The average reproduction rate for all crops in Germany is 12 %. For wheat, the regrowth rate in Central Europe is 15.52 %. In order to estimate the reproduction rate of organic winter wheat, a survey was carried out among four organic wheat breeders: The Keyserlingk Institute and “Salem” assumed an average 3-year reproduction period. “Getreidezüchtung Peter Kunz” (GZPK) and “Forschung & Züchtung Dottenfelderhof” (FZD) anticipated one-time regrowth. They reported 1,500 t of seed sold from organic varieties in 2022. With an average sowing rate of 200 kg/ha, this results in a cultivated area of 7,500 ha. The cultivation area of the organic varieties of the GZPK and FZD therefore results in an area of approx.15,000 ha in Germany. The approximations show the problem of the lack of labelling of organic varieties. Based on the above calculations, an area share for organic wheat from organic varieties of at least 9,044.69 ha (0.6 % of the total common winter wheat quantity of 261,267.52 t) can be assumed. However, the actual amount is probably significantly higher. A standardized labelling of organic varieties is necessary.

An increasing demand for organic seeds in Europe

In addition to the problem that estimates are difficult due to the lack of labelling, organic varieties have two disadvantages compared to conventional seed: a higher price of seed procurement and a lower crop yield. The LIVESEED report (2019) evaluates several European studies and shows that farmers do not see the higher price of organic seed as an obstacle to working with it. But the European Commission's Agricultural Market and Income Outlook for Europe (European Union, 2018) shows clear differences in yield between the two seed classes, which can act as a deterrent for many farmers to convert to organic farming and counteract to the aim of sustainable intensification. To evaluate the development of demand for organic seeds and the current product range, Lukas Meysen (2022) conducted a survey of companies in the German crop seed market as part of his state examination thesis within our study. For this purpose, 52 companies based in Germany and abroad were contacted that are active on the German seed market and are involved in the breeding process, propagation or distribution of varieties that are authorized for the German seed market. This was limited to wheat, triticale, emmer, einkorn and spelt in order to achieve a better fit with the study results of the vegetation survey. The demand for organic seeds of category 1 and 2 is expected to increase over the next ten years according to Euroseeds (2019). The same is predicted by the majority of participants in the survey on the German crop seed market: 90 % of participants believe that the demand for category 1 seeds will increase in the next 10 years, 68.4 % predict an increase in demand for category 2 seeds. One of the main reasons for working with organic varieties was the current and (Europe, 2019a, 2019b) future market opportunities, which leads to the suggestion that most seed producers already include organic seeds in their planning. The increasing demand for seeds that are propagated according to organic certification criteria could lead to an increase in organic farming (Meysen, 2022), which again could impact the biodiversity of agricultural ecosystems in a positive way.

Genome-edited seeds as recommendation of the IPCC

While there are many unanswered questions in the case of eco-varieties, others propose contrary methods: intensive agriculture could be practiced on conventional land, maximizing yields, while organic land could provide a balance in terms of biodiversity or be renatured. According to Maurer (2022), this would increase biodiversity more than a complete conversion to organic farming. Maximizing yields on conventional land can also be achieved by adapting the species to the local existing climate. Kellermann (2020) suggests particularly high-yielding species that have acquired resistance through genetic engineering. According to Squire et al. (2005), 20 to

30 more weeds per m² can grow in a field with genetically modified wheat without any significant loss in yield.

The survey results of the study by Meysen (2022) show that 82 % of participants see genome editing as an opportunity for the breeding process. Currently, genome editing is used worldwide primarily to increase the herbicide tolerance of species, but it also plays an important role in terms of insect tolerance (Kellermann, 2020). But genome-edited seeds are banned on the European market and it is uncertain whether this will change in the future. However, 64 % of the participants (n = 22) agreed with the statement that a long-term integration of genome editing into the breeding process is possible for the European market. This result raises the question of whether a corresponding regulation could be introduced in the near future, but is also dependent on public opinion. In the discussions about genome-edited seeds in the past, ethical concerns were raised in particular, which run counter to the technical advantages of the methods (Kellermann, 2020). A clear statement regarding the future of genome-edited seed cannot be made for the European market, but the results of the survey suggest that the majority of companies active in the seed market consider the integration of genome-editing in the European market to be possible (Euroseeds, 2019; Meysen, 2022).

The latest IPCC Special Report (2019) emphasizes this and states, that progress in plant breeding is crucial for improving food security under changing climatic conditions. It further advises improving genetics to give crops greater drought and heat tolerance and improve water and nutrient efficiency. Genome editing, or CRISPR-Cas, is explicitly mentioned as an option for higher yields. It allows precise interventions in the genetic material of the plant so that breeders are no longer dependent on random chance but can make targeted changes (Massel et al., 2021). In addition, linked inherited genes can be addressed, which does not work with crossbreeding. This saves up to ten years in the breeding process, depending on the crop. Although genome editing only changes the plant's genetic material in a way that could have occurred naturally, i.e. the plant does not contain any foreign genetic material, this technique is still not permitted in the EU. The IPCC report also includes numerous other recommendations based on many studies relating to consumer behaviour and the world population's dietary habits, with the aim of reducing food waste and making technical improvements in agriculture. Sustainable soil cultivation without ploughing is also mentioned, as is already being carried out by some farmers in my study and discussed above. Additionally, the report mentions better access to adapted seeds and technical aids, which were also wishes of the participating farmers, as will soon be published in the evaluations of the political surveys.

4.3 Other options to promote plant biodiversity in agricultural landscapes

While decisions on genome-edited seeds and the labelling of organic varieties are in the hands of politicians, there are also many approaches that farmers themselves can take to make their farming practices more sustainable. By adapting traditional agricultural practices to the current needs of our environment, we can protect the accompanying weed biodiversity. Rather than relying solely on herbicides, there are other weed management strategies, with which the yield can be secured and still help conserve weed biodiversity. Certain weed species can even be beneficial for the soil and the crop, and can be encouraged through management practices that favour their growth. Monitoring weed communities on the field over time can help identify changes in weed diversity and distribution. Using a diverse crop rotation, including cover crops and intercropping, can reduce weed pressure and increase the diversity of weed species on the field. Besides, it saves the soil from being too depleted by monocultures. In a literature review, Cozim-Melges et al. (2024) summarised various farming practices for enhancing biodiversity in different biomes and assessed their impact as positive, negative or neutral. While some practices had contrasting effects on different taxa, the avoidance of pesticides achieved almost exclusively positive results.

Additional to protective measures on the field, there are other ideas on how to preserve rare and endangered plant species. For example, their reintroduction through seed is being considered (Albrecht et al., 2016; Lang et al., 2016; Meyer, 2020): rare plants can be pre-grown and planted out. However, according to Albrecht and McCue (2010), this does not work well; only few of the seedlings manage to establish themselves. Little is also known about the long-term effectiveness of this method. Selectively sowing rare weeds has the advantage, similar to pre-growing, that species can be selected flexibly and applied in regulated quantities. Problem weeds are avoided, but no fixed plant communities are created, and there are strong selection effects due to the age and dormancy of the seeds. The transfer of mown grass or simply to refrain from seed cleaning are two more approaches to promoting diversity in fields, but in contrast to selective sowing, problem weeds are likely to suppress rare weeds. In addition, in all above mentioned attempts, there is no transmission of microorganisms. This would be circumvented by soil transfer, but only small distances can be managed with this method. All of the mentioned options are worth trying to repair the damage that has already been done to arable biodiversity. However, it is certainly no substitute for protecting the remaining arable flora.

Alternative methods of meeting our high demand for food while using more sustainable, biodiversity-friendly farming methods are constantly being developed. From the idea of growing plants completely without soil under sterile laboratory conditions (Sharma et al., 2018), so as not to need any pesticides and to act exactly according to the needs of the plant, to agroforestry systems (AlShrouf, 2017), a wide variety of research groups are looking for the ideal cultivation method. Agroforestry systems seem to offer a promising approach for many regions of the world. Here, trees are usually planted in rows between relatively narrow strips of arable land, and therefore serve as a source of shade, windbreak and, due to the significantly deeper rooting, also enhance the soil (Cardinael et al., 2020). Due to that and the improved water balance thanks to shading and less evaporation, even higher yields are usually recorded on research fields than on comparative fields without trees (Kanzler et al., 2019).

Lenerz et al. (2017) propose conservation fields and field flora reserves. The latter were anticipated in the project "100 Fields for Diversity" (Meyer & Leuschner, 2015). On conservation fields, no herbicides and fertilizers are applied, the stubble is ploughed later and there are no catch crops, which are normally applied after harvest to quickly cover the soil and thus prevent weeds from emerging. Specifically, the fields on which rare species have already been found are farmed more extensively, allowing these species to be preserved. These primarily include fields that differ from most other agricultural areas, such as particularly calcareous or acidic soils. A model for this project was the field flora reserve on the Beutenlay near Münsingen in the Swabian Alb, which has existed since 1970. Its main purpose is to preserve the species that are native to limestone fields.

One possibility that may become more important in the future, once the costs of acquisition and high energy requirements have fallen, is laser weeding. As reviewed by Andreasen et al. (2022), in a few years it could be possible to specifically combat problem weeds with the laser without harming non-target organisms, while in turn creating more space for them.

Finding the best possible management for each region is a long process and certainly there is no ideal solution. A mixture of different methods offers wildlife and plants the opportunity to avoid negative influences and to find suitable niches for them. Involving farmers in the process and responding to their needs is important. The recent protests across Germany, in which tens of thousands of farmers blocked roads with their farming machinery, not only show the discontent against the cancellation of subsidies granted for agricultural diesel and vehicle tax in forestry and agriculture. It also displays how much dissatisfaction has built up among farmers, who do not feel valued by both the government and the general public (Heinze et al., 2021). To achieve greater sustainability and climate protection in agriculture, it is therefore essential to actively involve farmers in decision-making processes in order to take their interests and needs into account, for example through local working groups, dialogue forums or public participation processes. This also facilitates the creation of the right financial support systems and advisory services, as well as market integration.

5 Conclusion

We need to move away from trying to find an optimal solution and from treading water in the attempt. Many measures bring about small advances in the protection of biodiversity and should be strived for and promoted accordingly.

A close collaboration must happen between all stakeholders, especially policymakers and farmers to develop effective support strategies, including continuous monitoring and evaluation of all policies and programs to ensure their effectiveness. All participants along the chain of food production and commercial exploitation have to be included in the transformation process. These strategies may include provision of support and training for farmers who want to transition to organic methods, including market information and technical assistance, as well as financial incentives and regulatory support, e.g. by implementing subsidies, tax incentives or supporting trade policies. Providing farmers with information about the benefits of biodiversity and the role it plays in sustainable agriculture can help to raise awareness and build interest in the topic. Through the establishment of demonstration farms, the benefits of incorporating biodiversity into farming systems can be effectively shown in action. Building networks of farmers who are interested in biodiversity can provide opportunities for sharing information and experiences, and help to foster a sense of community and collaboration. Collaboration with private sector organizations, such as seed companies and agribusinesses, can provide farmers with access to the resources and expertise they need to adopt and integrate biodiversity-friendly practices into their operations.

Parallel to that, markets have to be developed: The demand of organic products must be further increased, on the one hand by educating consumers about the positive impact of organic farming practices on the environment and their own health and on the other hand by pointing out the dangers that come with biodiversity loss. As long as the inflation is writing bigger headlines than climate change and species extinction, the extent of the dangers does not yet seem to have reached the general public.

Lastly, investment in research on improving farming methods and developing new technologies is necessary. With a combination of all the aforementioned opportunities, it may be possible to bring about important changes in agriculture, where Baden-Württemberg can play a pioneering role. There is not one single, ideal way to save the world. In order to stop the biodiversity loss, countless small measures are needed, each of which may only affect a few species. However, the sum of all these measures might stop mass extinction. It is up to us to take action.

Acknowledgement

I would like to express my sincere gratitude to all the people who have accompanied and supported me over the past years of my dissertation. I would especially like to thank my doctoral supervisor Prof. Dr. Marcus Koch for his excellent supervision, support and many, many really helpful discussions and explanations.

I would also like to thank Prof. Dr. Jale Tosun, and Dr. Mike Thiv, who not only accompanied me as co-supervisors and on the Thesis Advisory Committee, but were always available for additional advice, and Charlene Marek, my co-doctoral candidate on this project on the political side for the cooperation, advice and friendship.

Furthermore, I would like to express my gratitude to the entire AG Koch, especially Dr. Peter Sack and Dr. Markus Kiefer for countless tips, long conversations and always an open ear; Dr. Nora Walden for patient guidance during the writing process; and to my fellow PhD students Alexandra Schöne, Sarina Jabbusch and Jonas Bleilevens for their friendship and for making fights with R (almost) fun (especially Alex!). Thanks, Cornelia Wiethaler, for coordinating contacts with the organic farmers and extensive research on organic varieties.

Thanks to all cooperation partners, particularly all farmers without whom there wouldn't be any data to evaluate! Many thanks to everyone who proofread this work for me, helped me with research or supported me in other ways.

Last but not least, I would like to thank the most important people in my life: my parents, my sister Marisa and my partner Julian, who support me in everything, always have my back and have provided encouragement, motivation or a kick in the ass at the right moments. I love you, endlessly.

List of Abbreviations

BAS	Botanische Arbeitsgemeinschaft Südwestdeutschland / Botanical Association of Southwest Germany
BSA	Bundessortenamt / Federal Plant Variety Office
DÜVO	Düngemittelverordnung / Fertilizer Ordinance
DWD	Deutscher Wetterdienst / German Weather Service
EMZ/dbEMZ	(durchschnittlich bereinigte) Ertragsmesszahlen / average adjusted yield measurement figures
FAKT	Förderprogramm für Agrarumwelt, Klimaschutz und Tierwohl / Support programme for agri-environment, climate protection and animal welfare
IFAB	Institut für Agrarökologie und Biodiversität e.V. / Institute for Agroecology and Biodiversity e.V.
IPCC	Intergovernmental Panel on Climate Change
LGRB	Landesamt für Geologie, Rohstoffe und Bergbau Baden-Württemberg / Baden-Württemberg State Office for Geology, Raw Materials and Mining
LTZ	Landwirtschaftliches Technologiezentrum Augustenberg / Augustenberg Agricultural Technology Centre
LUBW	Landesanstalt für Umwelt Baden-Württemberg / Baden-Württemberg State Institute for the Environment
LUFA	Landwirtschaftliche Untersuchungs- und Forschungsanstalten / Agricultural investigation and research institutes
MLR	Ministerium für Ernährung, Ländlichen Raum und Verbraucherschutz Baden-Württemberg / Ministry of Food, Rural Areas and Consumer Protection Baden-Württemberg
QZ	Qualitätszeichen Baden-Württemberg / Baden-Württemberg quality mark
URZ	Universitäres Rechenzentrum / University Computer Centre
VLOG	Verband “Lebensmittel ohne Gentechnik” e.V. / Association “Food without Genetic Engineering” registered association
w.V.	wirtschaftlicher Verein / economic association

List of Figures

List of Tables

List of Supplements

Supplements attached to the document:

Supplement 1: List of the organic varieties classified by BSA (as of 19 July 2023). The varieties marked in green were sown in the studied fields (Descriptive Variety List 2023, BSA)

Supplement 2: List of all varieties used by ecological farmers within this study, that are not registered as organic varieties with the BSA

The additional data CD contains the following files:

Name of the document/folder	**Description**
80_species_list.xlsx	list of 80 representative wild plant species for arable fields (compiled by (i) selecting characteristic flora species of arable fields (Pierny, 1994), (ii) excluding very locally distributed species, and (iii) excluding taxa that were not yet taxonomically well defined)
100_most_frequent_species_bawü.xlsx	100 most frequent species in Baden-Württemberg as recorded in FloraBW
agrobiodivherbarbelege.xlsx	List of all sampled herbarium vouchers
all species incl red list status and ellenberg values.xlsx	List of all species found including scientific and German name, Ellenberg indicative values, biontic status, Status in the Red List and nature conservation significance as of Breunig and Demuth (2023)
data_R_script.xlsx	Complete list of all studied fields including all factors and additional data
for_PCA.xlsx	Excel document for conducting PCA analyses in R
mapping_template_2022.pdf	Template for mapping, 2022
normal distribution plots (folder)	Plots of statistical testing of normal distribution of Shannon Index and number of species found on each field
R_Script_Thesis.R	R script used for statistics and graphs
summaryofPCA.txt	Summary of PCA results including Eigenvalues

Reference List

Adeux, G., Vieren, E., Carlesi, S., Bàrberi, P., Munier-Jolain, N., & Cordeau, S. (2019). Mitigating crop yield losses through weed diversity. *Nature Sustainability*, *2*(11), 1018-1026.

Ahlmann-Eltze, C., & Patil, I. (2021). ggsignif: R Package for Displaying Significance Brackets for'ggplot2'.

Agrarmarkt Informations-Gesellschaft mbH. (AMI) (2022). Erlöse mit Bio-Produkten 2021 zweistellig gewachsen. Agrarmarkt Informations-Gesellschaft mbH. https://www.ami-informiert.de/ami-maerkte/maerkte/ami-maerkte-oekolandbau/meldungen/single-ansicht?tx_aminews_singleview%5Baction%5D=show&tx_aminews_singleview%5Bcontroller%5D=News&tx_aminews_singleview%5Bnews%5D=37995&cHash=8be23aef6bd7d8146d07306ec20e8c2f (accessed 02.02.2024)

Albkorn (2024). Erzeugerregeln für Albkorn. https://albkorn.de/albkorn/erzeugerregeln/ (accessed 19.01.2024)

Albrecht, C., Esser, T., & Hille, B. (2008). Wirksamkeit und Fördermöglichkeiten von Zusatzstrukturen in der Landwirtschaft als Beitrag zum Erhalt der Artenvielfalt; Literaturstudie im Auftrag des Deutschen Jagdschutz-Verbandes eV. *Ilu*.

Albrecht, H., Cambecèdes, J., Lang, M., & Wagner, M. (2016). Management options for the conservation of rare arable plants in Europe. *Botany Letters*, *163*(4), 389-415.

AlShrouf, A. (2017). Hydroponics, aeroponic and aquaponic as compared with conventional farming. *Am. Sci. Res. J. Eng. Technol. Sci*, *27*(1), 247-255.

Altieri, M., & Nicholls, C. (2018). Biodiversity and pest management in agroecosystems. *CRC press.*

Aphalo, P. J. (2016). ggpmisc: An R package.

Ashida, A. (2014). The Convention on Biological Diversity and National Biodiversity Strategy and Action Plans in Germany and Japan. Technische Universität München.

Assmann, T., Drees, C., Härdtle, W., Klein, A., Schuldt, A., & von Oheimb, G. (2014). Ökosystem und Biodiversität. *Nachhaltigkeitswissenschaften*, 147-174.

Auguie, B., Antonov, A., & Auguie, M. B. (2017). Package ‘gridExtra’. *Miscellaneous Functions for “Grid” Graphics*.

Bache, S. M., Wickham, H., Henry, L., & Henry, M. L. (2022). Package ‘magrittr’. *R. Package Version*.

Badgley, C., & Perfecto, I. (2007). Can organic agriculture feed the world? *Renewable Agriculture and Food Systems*, *22*(2), 80-86.

Balbuena, M. S., Tison, L., Hahn, M.-L., Greggers, U., Menzel, R., & Farina, W. M. (2015). Effects of sublethal doses of glyphosate on honeybee navigation. *The Journal of experimental biology*, *218*(17), 2799-2805.

Bartier, P. M., & Keller, C. P. (1996). Multivariate interpolation to incorporate thematic surface data using inverse distance weighting (IDW). *Computers & Geosciences*, *22*(7), 795-799.

Bengtsson, J., Ahnström, J., & Weibull, A. C. (2005). The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *Journal of applied ecology*, *42*(2), 261-269.

Benvenuti, S., & Bretzel, F. (2017). Agro-biodiversity restoration using wildflowers: What is the appropriate weed management for their long-term sustainability?. *Ecological Engineering*, *102*, 519-526.

Brasseur, G. P., Jacob, D., & Schuck-Zöller, S. (2017). Klimawandel in Deutschland: Entwicklung, Folgen, Risiken und Perspektiven. *Springer Nature.*

Braun-Blanquet, J. (2013). Pflanzensoziologie: Grundzüge der Vegetationskunde. *Springer-Verlag.*

Breunig, T. (2002). Rote Liste der Biotoptypen Baden-Württembergs. *Naturschutz Landschaftspflege Baden-Württemberg*, *74*, 259-307.

Breunig, T., & Demuth, S. (2023). Rote Liste der Farn-und Blütenpflanzen Baden-Württembergs. *LUBW Landesanstalt für Umwelt Baden-Württemberg 2*.

Brockerhoff, H. (2015). Winterweizen: Qualitätsgruppen und Verwertungsrichtungen bei den Winterweizensorten. Landwirtschaftskammer Nordrhein-Westfahlen. https://www.landwirtschaftskammer.de/landwirtschaft/ackerbau/getreide/winterweizen-infos-pdf.pdf (accessed 25.01.2024).

Bundesamt für Naturschutz (2022). Monitoring von Landwirtschaftsflächen mit hohem Naturwert. https://www.bfn.de/monitoring-von-landwirtschaftsflaechen-mit-hohem-naturwert (accessed 31.01.2024)

Bundesanstalt für Landwirtschaft und Ernährung (BLE). (2023). Besondere Ernte- und Qualitätsermittlung (BEE) 2022. https://www.ble.de/SharedDocs/Downloads/DE/BZL/Daten-Berichte/Getreide_Getreideerzeugnisse/BEE_2022.pdf (accessed 31.01.2024)

Bundesinformationszentrum Landwirtschaft (2024). Erträge von Bio-Getreide halb so groß. AMI. https://www.bzl-datenzentrum.de/umwelt-und-klima/oekolandbau#c7435 (accessed 31.01.2024)

Bundesinformationszentrum Landwirtschaft (2024). Wie stark sind die Erträge von Nutzpflanzen seit 1950 gestiegen? https://www.praxis-agrar.de/service/infografiken/wie-stark-sind-die-ertraege-von-nutzpflanzen-seit-1950-gestiegen (accessed 04.03.2024)

Bundesministerium für Ernährung und Landwirtschaft (BMEL). (2023). Bio-Strategie 2030. Nationale Strategie für 30 Prozent ökologische Land- und Lebensmittelwirtschaft bis 2030. BMEL.de https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/bio-strategie-2030.pdf (accessed 03.01.2024)

Bundessortenamt (BSA) (2021). Anerkannte Saatgutmengen (dt) 2021 (Wirtschaftsjahr 2021/2022). https://www.bundessortenamt.de/bsa/media/Files/Saatgut/P1_anerkMengen_LW_Art_20220818.pdf (accessed 11.11.2023)

Bundessortenamt (BSA) (2023). Aufgaben des Bundessortenamts. https://www.bundessortenamt.de/bsa/das-bsa/aufgaben (accessed 13.12.2023).

Cardinael, R., Mao, Z., Chenu, C., & Hinsinger, P. (2020). Belowground functioning of agroforestry systems: recent advances and perspectives. *Plant and Soil*, *453*, 1-13.

Catt, J. A. (2001). The agricultural importance of loess. *Earth-Science Reviews*, *54*(1-3), 213-229.

Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science*, *333*(6045), 1024-1026.

Cozim-Melges, F., Ripoll-Bosch, R., Veen, G. F., Oggiano, P., Bianchi, F. J., van der Putten, W. H., & van Zanten, H. H. (2024). Farming practices to enhance biodiversity across biomes: a systematic review. *npj Biodiversity*, *3*(1), 1.

De Ponti, T., Rijk, B., & Van Ittersum, M. K. (2012). The crop yield gap between organic and conventional agriculture. *Agricultural systems*, *108*, 1-9.

Devadoss, S., & Ridley, W. (2024). Impacts of the Russian invasion of Ukraine on the global wheat market. *World Development*, *173*, 106396.

Díaz, S. M., Settele, J., Brondízio, E., Ngo, H., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K., & Butchart, S. (2019). The global assessment report on biodiversity and ecosystem services: Summary for policy makers.

Dohrn, S. (2017). Das Ende der Natur: die Landwirtschaft und das stille Sterben vor unserer Haustür (Vol. 10193). Ch. Links Verlag.

DV ÖkoPZ (2024). Dachverband Ökologische Pflanzenzüchtung in Deutschland e.V. Definition ökologische Pflanzenzüchtung. https://www.dv-oekopz.org/downloads/Definition_oekologische_Pflanzenzuechtung_012023.pdf (accessed 31.01.2024)

Europe, I. O. (2019a). Report on relative importance of factors encouraging or discouraging farmers to use organic seed in organic supply chains. *LIVESEED Project Report*.

Europe, I. O. (2019b). State of the art of existing breeding initiatives & actions planned to strengthen collaborations. *LIVESEED Project Report*.

Euroseeds. (2019). Report. Seeds for Organic Farming. Survey Results. *Brüssel: Euroseeds*.

Fischer, R. A., Ramos, O. M., Monasterio, I. O., & Sayre, K. D. (2019). Yield response to plant density, row spacing and raised beds in low latitude spring wheat with ample soil resources: an update. *Field crops research*, *232*, 95-105.

Flora Naturkundemuseum (2023). Die TOP 100: die häufigsten Pflanzenarten im Land. Stand April 2023. https://flora.naturkundemuseum-bw.de/Die%20TOP%20100_2023.pdf (accessed 21.02.2024)

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., & West, P. C. (2011). Solutions for a cultivated planet. *Nature*, *478*(7369), 337-342.

Fuchs, H. & Schuhmacher, W. (2006). Vielfalt der Pflanzenwelt in der Agrarlandschaft. Schr. *R. des Instituts für Landwirtschaft und Umwelt*, *11*, 1-112.

Geologischer Dienst NRW (2019). Einteilung der Bodenarten. Landwirtschaftskammer Nordrhein-Westfalen. https://www.landwirtschaftskammer.de/lufa/pdf/bodenarten-einteilung.pdf (accessed 31.01.2024)

Gerhards, R., Dieterich, M., & Schumacher, M. (2013). Rückgang von Ackerunkräutern in Baden-Württemberg–ein Vergleich von vegetationskundlichen Erhebungen in den Jahren 1948/49, 1975–1978 und 2011 im Raum Mehrstetten–Empfehlungen für Landwirtschaft und Naturschutz. *Gesunde Pflanzen*, *65*(4), 151-160.

Gill, J. P. K., Sethi, N., Mohan, A., Datta, S., & Girdhar, M. (2018). Glyphosate toxicity for animals. *Environmental chemistry letters*, *16*, 401-426.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *Science*, *327*(5967), 812-818.

Gregorc, A., & Ellis, J. D. (2011). Cell death localization in situ in laboratory reared honey bee (Apis mellifera L.) larvae treated with pesticides. *Pesticide biochemistry and physiology*, *99*(2), 200-207.

Güngör, Ş. B. (2011). Measuring plant species diversity in alpine zones: a case study at the kazdaği national park, in turkey. *Archives of Biological Sciences*, *63*(4), 1147-1156.

Guyton, K. Z., Loomis, D., Grosse, Y., El Ghissassi, F., Benbrahim-Tallaa, L., Guha, N., Scoccianti, C., Mattock, H., & Straif, K. (2015). Carcinogenicity of tetrachlorvinphos, parathion, malathion, diazinon, and glyphosate. *The Lancet Oncology*, *16*(5), 490-491.

Heinze, R., Bieckmann, R., Kurtenbach, S. & Küchler, A. (2021). Bauernproteste in Deutschland: Aktuelle Einblicke und politische Verortung. *Forschungsjournal Soziale Bewegungen*, *34*(3), 360-379. https://doi.org/10.1515/fjsb-2021-0035

Hepperly, P., Douds Jr, D., & Seidel, R. (2006). The Rodale Institute Farming Systems Trial 1981 to 2005: long-term analysis of organic and conventional maize and soybean cropping systems. *Long-term field experiments in organic farming*, 15-31.

Hofmeister, H., & Garve, E. (1998). Lebensraum Acker. *Parey Hamburg*.

Infodienst Landwirtschaft (2024). Ertragsmesszahlen. https://lr.landwirtschaft-bw.de/,Lde/3650826_3651462_5405915_5378885_5378933_5394977 (accessed 11.11.2023)

IARC 05 (2017). IARC Monographs on the evaluation of carcinogenic risks to humans—volume 112: some organophosphate insecticides and herbicides. https://monographs.iarc.fr/wp-content/uploads/2018/07/mono112.pdf. (accessed 21.12.2022)

Intergovernmental Panel on Climate Change (IPCC) (2019). Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/srccl/download/

IPBES (2018). The IPBES assessment report on land degradation and restoration. *Zenodo*. https://doi.org/10.5281/zenodo.3237393

James, F. C., & Rathbun, S. (1981). Rarefaction, relative abundance, and diversity of avian communities. *The Auk*, *98*(4), 785-800.

Joormann, I., & Schmidt, T. G. (2017). FRANZ-Studie–Hindernisse und Perspektiven für mehr Biodiversität in der Agrarlandschaft. *Ag.Econ.*

Júnior, R. D. S. N., Ewert, F., Webber, H., Martre, P., Hertel, T. W., van Ittersum, M. K., & Asseng, S. (2022). Needed global wheat stock and crop management in response to the war in Ukraine. *Global Food Security*, *35*, 100662.

Kanzler, M., Böhm, C., Mirck, J., Schmitt, D., & Veste, M. (2019). Microclimate effects on evaporation and winter wheat (*Triticum aestivum* L.) yield within a temperate agroforestry system. *Agroforestry systems*, *93*, 1821-1841.

Kassambara, A. (2020a). ggpubr:“ggplot2” based publication ready plots. *R package version 0.4. 0*, *438*.

Kassambara, A. (2020b). rstatix: Pipe-friendly framework for basic statistical tests. *R package version 0.6.0*.

Kaule, G. (1991). Arten-und Biotopschutz, zweite überarbeitete Auflage. *Verlag Eugen Ulmer, Stuttgart*.

Kellermann, K. (2020). Die Zukunft der Landwirtschaft: Konventioneller, gentechnikbasierter und ökologischer Landbau im umfassenden Vergleich. *Springer-Verlag*.

Koch, M. A., Tosun, J., Kellermann, L., Marek, C., Kiefer, M., & Thiv, M. (2023). Reducing pesticides without organic certification? Potentials and limits of an intermediate form of agricultural production. *Cogent Food & Agriculture*, *9*(1), 2202892.

Kolodziejek, J. (2018). Seed Dormancy in Cereal Weed *Adonis flammea* Jacq. (Ranunculaceae). *Journal of Agricultural Science and Technology*, *20*(1), 109-120.

Korneck, D., & Sukopp, H. (1988). Rote Liste der in der Bundesrepublik Deutschland ausgestorbenen, verschollenen und gefährdeten Farn-und Blütenpflanzen und ihre Auswertung für den Arten-und Biotopschutz. *Bundesforschungsanstalt für Naturschutz und Landschaftsökologie.*

Kraichgau Korn (2024). Was macht Kraichgaukorn® aus? https://kkhomepage.kraichgaukorn.de/kraichgaukorn-informationen-zur-landwirtschaft/ (accessed 19.01.2024)

Kühn, N., & Pfadenhauer, J. (1995). Anwendungsmöglichkeiten für Diversitätsindizes im Grünland. 24. *Verhandlungen der Gesellschaft für Ökologie*, *24*, 661-666.

Lafond, G. P. (1994). Effects of row spacing, seeding rate and nitrogen on yield of barley and wheat under zero-till management. *Canadian Journal of Plant Science*, *74*(4), 703-711.

Landesanstalt für Landwirtschaft, Ernährung und Ländlichen Raum Schwäbisch Gmünd (LEL) (2024). Abbildungen zur ökologischen Landwirtschaft. https://lel.landwirtschaft-bw.de/,Lde/Startseite/Service_+Downloads/Oekologische+Landwirtschaft (accessed 09.02.2024)

Lang, M., Prestele, J., Fischer, C., Kollmann, J., & Albrecht, H. (2016). Reintroduction of rare arable plants by seed transfer. What are the optimal sowing rates? *Ecology and Evolution*, *6*(15), 5506-5516.

LGRB-BW BÜK200: Nitratauswaschung. https://gdk.gdi-de.org/geonetwork/srv/api/records/f59c9d5b-acc4-4b13-bde1-9c694bcb568a (accessed 19.01.2024)

Linzgaukorn (2024). Karte von Linzgau Korn. https://www.linzgaukorn.de/ (accessed 31.01.2024)

Linzgau Korn (2024). Richtilinien – Beste Qualität in Anbau und Verarbeitung. https://www.linzgaukorn.de/#Richtlinien (accessed 19.01.2024)

LTZ (2023). Vermehrungsflächen in Baden-Württemberg 2023 in ha. https://ltz.landwirtschaft-bw.de/site/pbs-bw-mlr-root/get/documents_E-75679790/MLR.LEL/PB5Documents/ltz_ka/Arbeitsfelder/Saatgutanerkennung/Statistiken_DL/Vermehrungsfl%C3%A4chen%20nach%20Arten%20%C3%B6ko-konv%202023.pdf (accessed 09.11.2023)

Meyer, S. (2020). The status of arable plant habitats in Central Europe. The Changing Status of Arable Habitats in Europe: *A Nature Conservation Review*, 55-73.

Meyer, S., & Leuschner, C. (2015). 100 Äcker für die Vielfalt. *Universitätsverlag Göttingen*.

Meynen, E., Schmithüsen, J., Gellert, J., Neef, E., Müller-Miny, H., & Schultze, J. H. (1962). Handbuch der naturräumlichen Gliederung Deutschlands. In *Bd.* (Vol. 2). Bad Godesberg.

Meysen, L. (2022). Bedeutung und Potenzial der ökologischen Zuchtforschung für den Schutz der Biologischen Vielfalt. Unpublished undergraduate thesis, Universität Heidelberg.

Millard, J., Outhwaite, C. L., Kinnersley, R., Freeman, R., Gregory, R. D., Adedoja, O., Gavini, S., Kioko, E., Kuhlmann, M., & Ollerton, J. (2021). Global effects of land-use intensity on local pollinator biodiversity. *Nature Communications*, *12*(1), 2902.

MLR (2017). FAKT Förderprogramm für Agrarumwelt, Klimaschutz und Tierwohl Baden-Württemberg. Ministerium für Ernährung, Ländlichen Raum und Verbraucherschutz. https://mlr.baden-wuerttemberg.de/fileadmin/redaktion/m-mlr/intern/dateien/publikationen/Landwirtschaft/2017_Fakt_Foerderprogramm_Agrarumwelt_Klimaschutz_Tierwohl.pdf (accessed 25.01.2024).

Navntoft, S., Kristensen, K., Johnsen, I., Jensen, A.-M.M., Sigsgaard, L. and Esbjerg, P. (2016), Effects of weed harrowing frequency on beneficial arthropods, plants and crop yield. Agr Forest Entomol, 18: 59-67. https://doi.org/10.1111/afe.12134

Pedersen, T. L. (2019). Package ‘patchwork’. *R package http://CRAN. R-project. org/package= patchwork. Cran*.

Pentz, W. (1960). Die Steigerung der deutschen Getreideerträge. *German Journal of Agricultural Economics/Agrarwirtschaft*, *9*(4), 125-139.

Pierny, M. (1994). Bestandsaufnahme zum aktuellen Entwicklungszustand der Ackerbegleitflora und ihre räumliche Differenzierung in Baden-Württemberg: Erstellung eines regionalisierten Bedarfs-und Maßnahmenkonzepts zu Erhalt, Entwickung und Regeneration des zurückgehenden und gefährdeten Anteils der Ackerbegleitflora in Baden-Württemberg; Studie im Auftrag des Landesamtes für Flurneuordnung und Landentwicklung Baden-Württemberg. *Institut für Landschaftsplanung und Ökologie, Universität Stuttgart.*

Ponisio, L. C., M'Gonigle, L. K., Mace, K. C., Palomino, J., De Valpine, P., & Kremen, C. (2015). Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1799), 20141396.

QGIS Development Team (2022). QGIS Geographic Information System. Open Source Geospatial Foundation Project. https://www.qgis.org. (accessed 06.08.2022)

Regierungspräsidium Freiburg, Landesamt für Geologie, Rohstoffe und Bergbau (2021). LGRB-Kartenviewer, https://maps.lgrb-bw.de/ (accessed 22.11.2023)

Rennwald, E., Bartram, T., Berg, C., Bergmeier, E., Bettinger, A., Blümel, A., Bohn, U., Böhnert, W., Brandes, D., Breunig, T., Burkart, M., Bushart, M., Dengler, J., Dierschke, H., Dierßen, K., Dinter, W., Dörr, E., Drachenfels, O., Ewald, J., & Zahlheimer, W. (2002). Rote Liste der Pflanzengesellschaften Deutschlands mit Anmerkungen zur Gefährdung. *Schriftenreihe für Vegetationskunde*, *35*, 393-592.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Rockström,

J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/doi:10.1126/sciadv.adh2458

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., & Schellnhuber, H. J. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472-475.

Rosic, N., Bradbury, J., Lee, M., Baltrotsky, K., & Grace, S. (2020). The impact of pesticides on local waterways: A scoping review and method for identifying pesticides in local usage. *Environmental Science & Policy*, *106*, 12-21.

Schrama, M., De Haan, J., Kroonen, M., Verstegen, H., & Van der Putten, W. (2018). Crop yield gap and stability in organic and conventional farming systems. *Agriculture, ecosystems & environment*, *256*, 123-130.

Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, *485*(7397), 229-232.

Sharma, N., Acharya, S., Kumar, K., Singh, N., & Chaurasia, O. P. (2018). Hydroponics as an advanced technique for vegetable production: An overview. *Journal of Soil and Water Conservation*, *17*(4), 364-371.

Statistisches Landesamt Baden-Württemberg (2021). Entwicklung der Betriebsgrößenstruktur. https://www.statistikbw.de/Landwirtschaft/Agrarstruktur/Betriebe-LFGK.jsp (accessed 16.09.2021).

Statistisches Landesamt Baden-Württemberg (2021). Landwirtschaftszählung 2020 – Ökologische Landwirtschaft. Statistik Aktuell. https://www.statistik-bw.de/Service/Veroeff/Statistik_AKTUELL/803421004.pdf (accessed 31.01.2024)

Tosun, J., & Varone, F. (2021). Politicizing the use of glyphosate in Europe: Comparing policy issue linkage across advocacy organizations and countries. *Journal of Comparative Policy Analysis: Research and Practice*, *23*(5-6), 607-624.

Tscharntke, T., Clough, Y., Wanger, T. C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J. & Whitbread, A. (2012a). Global food security, biodiversity conservation and the future of agricultural intensification. *Biological conservation*, *151*(1), 53-59.

Tscharntke, T., Grass, I., Wanger, T. C., Westphal, C., & Batáry, P. (2021). Beyond organic farming–harnessing biodiversity-friendly landscapes. *Trends in ecology & evolution*, *36*(10), 919-930.

Tscharntke, T., Tylianakis, J. M., Rand, T. A., Didham, R. K., Fahrig, L., Batáry, P., Bengtsson, J., Clough, Y., Crist, T. O., & Dormann, C. F. (2012b). Landscape moderation of biodiversity patterns and processes-eight hypotheses. *Biological reviews*, *87*(3), 661-685.

Umweltbundesamt (UBA) (2021). Pesticides. https://www.umweltbundesamt.de/en/topics/soil-agriculture/ecological-impact-of-farming/pesticides (accessed 02.02.2023)

Umweltbundesamt (UBA) (2022). Umweltbundesamt. Gesellschaftliche Kosten von Umweltbelastungen. Umweltbundesamt. www.umweltbundesamt.de/daten/umwelt-wirtschaft/gesellschaftliche-kosten-von-umweltbelastungen#gesamtwirtschaftliche-bedeutung-der-umweltkosten (accessed 02.02.2023)

Umweltbundesamt (UBA) (2023). https://www.umweltbundesamt.de/daten/flaeche-boden-land-oekosysteme/flaeche/struktur-der-flaechennutzung#die-landwirtschaftlich-genutzte-flache-schrumpft (accessed 15.12.2023)

Van Elsen, T., Hotze, C., Meyer, S., Gottwald, F., & Wehke, S. (2009). Empfehlungen für die Bewirtschaftung von Schutzäckern. *University of Kassel: Kassel, Germany*.

Vittoz, P., & Guisan, A. (2007). How reliable is the monitoring of permanent vegetation plots? A test with multiple observers. *Journal of Vegetation Science*, *18*(3), 413-422.

Whittaker, R. H. (1972). Evolution and measurement of species diversity. *Taxon*, *21*(2-3), 213-251.

Wickham, H. (2011). ggplot2. *Wiley interdisciplinary reviews: computational statistics*, *3*(2), 180-185.

Wickham, H., Bryan, J., Kalicinski, M., Valery, K., Leitienne, C., Colbert, B., Hoerl, D., Miller, E., & Bryan, M. J. (2019). Package 'readxl'. *Version, 1.3, 1*.

Wickham, H., François, R., Henry, L., Müller, K., & Wickham, M. H. (2019). Package 'dplyr'. *A Grammar of Data Manipulation. R package version, 8*.

Wickham, H., & Wickham, M. H. (2017). Package 'tidyr'. *Easily Tidy Data with'spread'and'gather ()'Functions*.

Wörz, A., & Thiv, M. (2015). The temporal dynamics of a regional flora—The effects of global and local impacts. *Flora-Morphology, Distribution, Functional Ecology of Plants*, *217*, 99-108.

Wörz, A.; Voggesberger, M.; Abrahamczyk, S.; Krause, C.; Bildstein, U. & Thiv, M. (2024): Aktuelle Verbreitungskarten der Farn- und Blütenpflanzen Baden-Württembergs. http://www.flora.naturkundemuseum-bw.de. (accessed 22.02.2024)

Zhu, P., Burney, J., Chang, J., Jin, Z., Mueller, N. D., Xin, Q., Xu, J., Yu, L., Makowski, D., & Ciais, P. (2022). Warming reduces global agricultural production by decreasing cropping frequency and yields. *Nature Climate Change*, *12*(11), 1016-1023.

Zobiole, L., Kremer, R., Oliveira Jr, R., & Constantin, J. (2011). Glyphosate affects micro-organisms in rhizospheres of glyphosate-resistant soybeans. *Journal of applied microbiology*, *110*(1), 118-127.

Supplements

Supplement 3: List of the organic varieties classified by BSA (as of 19 July 2023). The varieties marked in green were sown in the studied fields (Descriptive Variety List 2023, BSA)

Nr.	Variety denomination	BSA ID number	Year of authorisation	Breeder number	Breeder name	Type recognition/ authorisation with BSA
1	**Adamus**	6454	2018	7414	Saatzucht Streng – Engelen GmbH & Co. KG	eligible for recognition §55
2	**Adesso**	4863	2016	9925	InterSaatzucht GmbH	Z
3	**Alessio**	5991	2016	7414	Saatzucht Donau Ges.m.b.H. & Co KG	eligible for recognition §55
4	**Annie**	5793	2014	6930	SELGEN, a. s.	eligible for recognition §55
5	**Argument**	5267	2018	4046	Saatzucht Streng – Engelen GmbH & Co. KG	Z
6	**Aristaro**	4873	2016	8266	Landbauschule Dottenfelderhof e.V.	SZ
7	**Asory**	5287	2018	1410	Secobra Recherches S.A.S.	Z
8	**Axioma**	4586	2014	1410	Secobra Recherches S.A.S.	Z
9	**Blickfang**	5957	2021	1410	Secobra Recherches S.A.S.	Z
10	**Brocken**	6396	2023	8856	Saatzucht Bauer GmbH & Co. KG	Z
11	**Butaro**	3768	2009	8266	Landbauschul Dottenfelderhof e.V.	SZ
12	**Campesino**	5470	2019	1410	Secobra Recherches S.A.S.	Z
13	**Castado**	5988	2021	8266	Landbauschul Dottenfelderhof e.V.	SZ
14	**Curier**	5412	2019	8266	Landbauschul Dottenfelderhof e.V.	SZ
15	**Edelmann**	6256	2017	5956	Landwirtschaftliche Fachschule Edelhof	eligible for recognition §55
16	**Effendi**	5402	2019	55	Saatzucht Firlbeck GmbH + Co. KG	Z
17	**Elixer**	4257	2012	25	W. von Borries-Eckendorf GmbH & Co. Kommanditgesellschaft	Z
18	**Genius**	3953	2010	9056	NORDSAAT Saatzuchtgesellschaft	Z
19	**Govelino**	4682	2015	10353	Cultivari Getreidezüchtungs-forschung Darzau gGmbH	Z
20	**Grannosos**	5694	2020	8266	Landbauschule Dottenfelderhof e.V.	Z
21	**Graziaro**	4872	2016	8266	Landbauschule Dottenfelderhof e.V.	SZ
22	**Informer**	5246	2018	8887	Saatzucht Josef Breun GmbH & Co. KG	Z
23	**Julius**	3580	2008	129	KWS LOCHOW GMBH	SZ
24	**KWS Essenz**	5263	2018	129	KWS LOCHOW GMBH	Z
26	**KWS Talent**	5088	2017	129	KWS LOCHOW GMBH	Z
27	**LG Exkurs**	6082	2022	1323	LIMAGRAIN GmbH (LG Europe-Research)	Z
28	**Moschus**	4923	2016	214	Herr Dr. Hermann Strube	Z
29	**Pizza**	4481	2012	9345	Getreidezüchtung P. Kunz	eligible for recognition §55
30	**Poesie**	4858	2015	9345	Getreidezüchtung P. Kunz	-
31	**Ponticus**	4736	2015	214	Herr Dr. Hermann Strube	Z

32	**Purino**	5285	2018	1410	Secobra Recherches S.A.S.	Z
33	**RGT Dello**	6329	2023	7352	R2n S.A.S. (Societe RAGT 2N)	Z
34	**Roderik**	5240	2018	10353	Cultivari Getreidezüchtungsforschung Darzau gGmbH	Z
35	**Royal**	4808	2015	9345	Getreidezüchtung P. Kunz	eligible for recognition §55
36	**Rübezahl**	6130	2022	1410	Secobra Recherches S.A.S.	Z
37	**Rubisko**	4980	2011	4417	(R.A.G.T.) Saaten Deutschland GmbH	eligible for recognition §55
38	**Sarastro**	5403	2019	10353	Cultivari Getreidezüchtungsforschung Darzau gGmbH	Z
39	**Senaturo**	5021	2017	4046	Saatzucht Streng - Engelen GmbH & Co. KG	
40	**Thomaro**	5355	2018	8266	Landbauschule Dottenfelderhof e.V.	SZ
41	**Tilliko**	5022	2017	10353	Cultivari Getreidezüchtungsforschung Darzau gGmbH	Z
42	**Tobias**	4983	2011	7414	Saatzucht Donau Ges.m.b.H. & Co KG	eligible for recognition §55
43	**Trebelir**	4842	2016	10353	Cultivari Getreidezüchtungsforschung Darzau gGmbH	Z
44	**Watzmann**	6398	2023	8856	Saatzucht Bauer GmbH & Co. KG	Z
45	**Wendelin**	5286	2018	1410	Secobra Recherches S.A.S.	Z
46	**Wital**	5516	2018	9345	Getreidezüchtung P. Kunz	eligible for recognition §55
47	**Wiwa**	3403	2005	7414	Getreidezüchtung P. Kunz	eligible for recognition §55

Supplement 4: List of all varieties used by ecological farmers within this study, that are not registered as organic varieties with the BSA

Nr.	Variety denomination	BSA ID number	Year of authorisation	Breeder number	Breeder name	Type recognition/ authorisation with BSA
48	**Alauda**	4800	2013	10756	Keyserlingk-Institut	Z + EHS
49	**Ataro**	3902	2004	9345	Getreidezüchtung P. Kunz	eligible for recognition §55
50	**Brandex Population**	5560	2022	8266	Landbauschule Dottenfelderhof e.V.	heterogeneous population, not recognised
51	**EQuality Population**	-	-	-	Dr. Odette Weedon	heterogeneous population, not recognised
52	**Goldritter**	4802	2013	10756	Keyserlingk-Institut	Z + EHS
53	**Hermion**	4525	2013	10756	Keyserlingk-Institut	Z + EHS
54	**Jagsttaler**	5399	2016	10493	Cornelia Kampmann	Z + EHS
55	**Jularo**	3769	appr. 2009 deleted 2021	8266	Landbauschule Dottenfelderhof e.V.	S + Z
56	**Kamperan**	5400	2016	10756	Keyserlingk-Institut	Z + EHS
57	**Kanzler**	976	appr. 1980 deleted 2005	508	Saatzucht ENGELEN	S + Z
58	**Philaro**	2841	appr. 2002 deleted 2010	3032	INAKTIV Syngenta Hadmersleben GmbH	Z
59	**SW Maxi**	4874	2016	8266	Landbauschule Dottenfelderhof e.V.	SZ
60	**Triptolemo**	5401	2016	10756	Keyserlingk-Institut	Z + EHS

Affidavit

GESAMTFAKULTÄT FÜR MATHEMATIK, INGENIEUR- UND NATURWISSENSCHAFTEN / COMBINED FACULTY OF MATHEMATICS, ENGINEERING AND NATURAL SCIENCES

Eidesstattliche Versicherung gemäß § 8 der Promotionsordnung der Gesamtfakultät für Mathematik, Ingenieur- und Naturwissenschaften der Universität Heidelberg

Sworn Affidavit according to § 8 of the doctoral degree regulations of the Combined Faculty of Mathematics, Engineering and Natural Sciences

1. Bei der eingereichten Dissertation mit dem Titel / The thesis I have submitted entitled "World Hunger versus Biodiversity – Transformation approaches towards a sustainable agricultural system" handelt es sich um meine eigenständig erbrachte Leistung. / is my own work.

2. Ich habe nur die angegebenen Quellen und Hilfsmittel benutzt und mich keiner unzulässigen Hilfe Dritter bedient. Insbesondere habe ich wörtlich oder sinngemäß aus anderen Werken übernommene Inhalte als solche kenntlich gemacht. / I have only used the sources indicated and have not made unauthorised use of services of a third party. Where the work of others has been quoted or reproduced, the source is always given.

3. Die Arbeit oder Teile davon habe ich bislang nicht an einer Hochschule des In- oder Auslands als Bestandteil einer Prüfungs- oder Qualifikationsleistung vorgelegt. / I have not yet presented this thesis or parts thereof to a university as part of an examination or degree.

4. Die Richtigkeit der vorstehenden Erklärungen bestätige ich. / I confirm that the declarations made above are correct.

5. Die Bedeutung der eidesstattlichen Versicherung und die strafrechtlichen Folgen einer unrichtigen oder unvollständigen eidesstattlichen Versicherung sind mir bekannt. / I am aware of the importance of a sworn affidavit and the criminal prosecution in case of a false or incomplete affidavit

Ich versichere an Eides statt, dass ich nach bestem Wissen die reine Wahrheit erklärt und nichts verschwiegen habe. / I affirm that the above is the absolute truth to the best of my knowledge and that I have not concealed anything.

…………………………………	……………………………..……
Ort und Datum / Place and date	Unterschrift / Signature