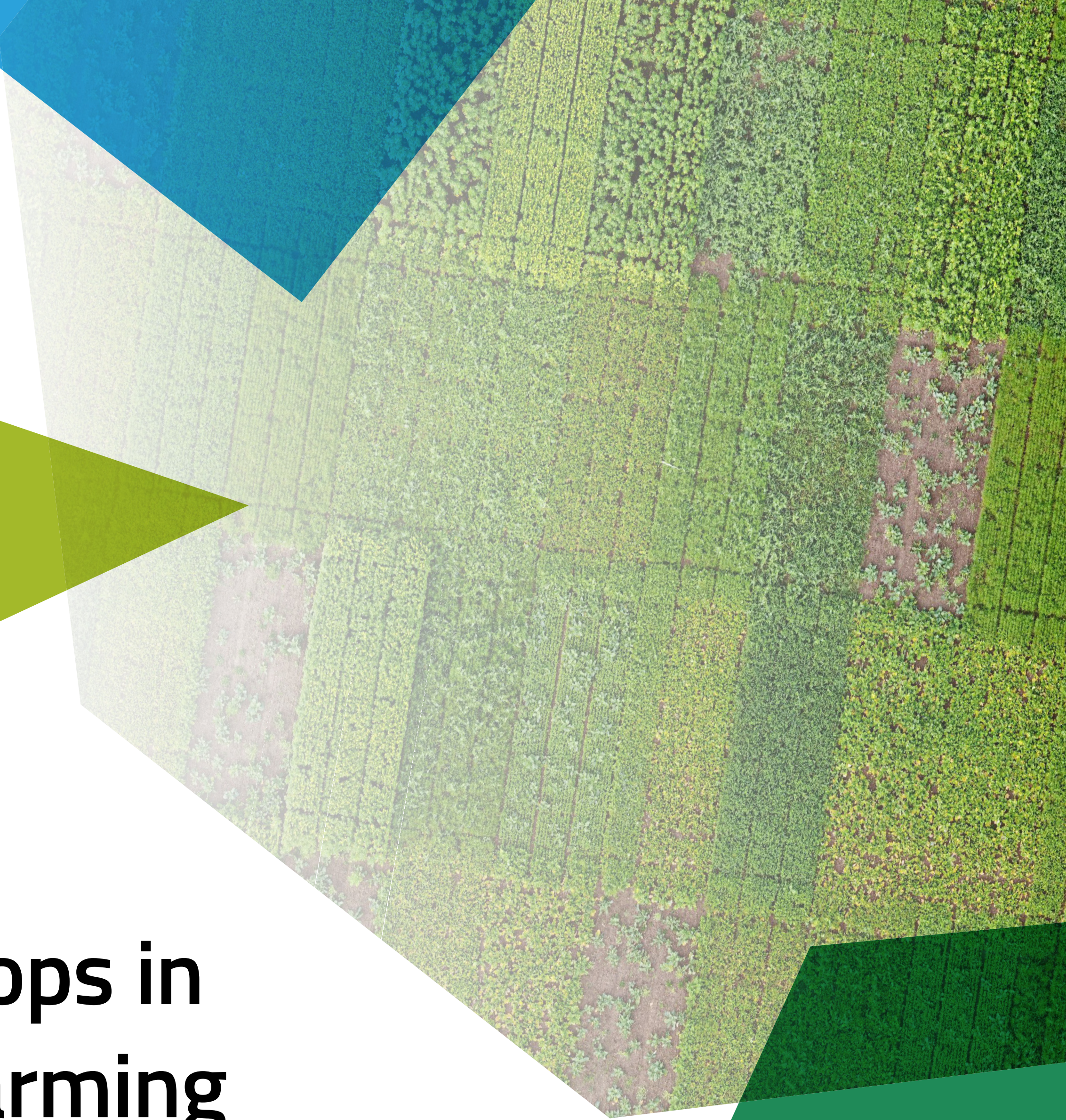


Cover crops in arable farming

Effects on soil structure, nutrient and water balance, microbiome, yields and profitability

Prof. Dr. Barbara Reinhold-Hurek[1], Dr. Thomas Hurek[1], Dr. Diana Heuermann[2], Prof. Dr. Nicolaus von Wirén[2], Dr. Norman Gentsch[3], Prof. Dr. Georg Guggenberger[3], Jonas Schön[4], Prof. Dr. Peter Breunig[4], Robin Kümmerer[4], Sophia Breische[5], Dr. Ulf Feuerstein[5], Carmen Fiedler[5], Jan Hendrik Schulz[5], Dörte Schweneker[5], Dr. Matthias Westerschulte[5], Michał Oskiera[1]

[1]University of Bremen, [2]Leibniz Institute of Plant Genetics and Crop Plant Research, [3]Leibniz University Hannover, [4]Weihenstephan-Triesdorf University of Applied Sciences, [5]Deutsche Saatveredelung AG

CATCHY

BONARES

SPONSORED BY THE
Federal Ministry of Education and Research

The CATCHY-Consortium:

University of Bremen	Department of Molecular Plant-Microbe Interactions
Leibniz University Hannover	Institute of Soil Science
Leibniz Institute of Plant Genetics and Crop Plant Research	Research Group for Molecular Plant Nutrition
Weihenstephan-Triesdorf University of Applied Sciences	Biomass Institute Plant Cultivation, Plant Protection and Grassland Biomass Institute Marketing, Market Theory
Deutsche Saatveredelung AG	Department of Research and Development Department of Biodiversity Product Management

CATCHY

BONARES

SPONSORED BY THE
Federal Ministry
of Education
and Research

Greeting

Dear Readers,

Soil is the basis of our existence. It fulfils a wide range of important functions for humans and the environment. Soil is a crucial resource for the production of food, animal feed and renewable raw materials for the industrial sector and energy production. By storing water and filtering out harmful substances, soil helps to prevent flooding and provides a supply of clean drinking water. Soil is also the biggest terrestrial carbon reservoir on Earth and thus plays a vital role in the fight against climate change. Moreover, soil is a habitat for a wide variety of organisms that play an important role when it comes to providing a sufficient nutrient supply for plants. It is, however, a resource that is very difficult to renew. As such, the goal of any type of soil use should be to maintain and preserve these functions. A large part of the responsibility here lies with the agricultural sector. In Germany, more than half of the country`s acreage is used by agriculture.

Agricultural soil systems with all the functions mentioned above have been the focus of the "Soil as a sustainable resource for the bioeconomy - BonaRes" initiative that was established in 2015 and is funded by the German Federal Ministry for Education and Research (BMBF). Ten research associations and the coordinating BonaRes Centre have spent the past nine years investigating how farmers can sustainably achieve high yields in the long term without negatively affecting other soil functions. The research associations work interdisciplinary and combine questions about fundamental soil science processes, from crop cultivation to the profitability of different cultivation systems. The main topics covered are: Optimizing soil functions, efficiency of water and nutrient usage and sustainably optimizing management strategies and usage management. One of the results of this project will be a set of recommendations for practical agriculture for sustainable soil management. Another special feature about the initiative is the duration of the funding over a total of nine years. This has made it possible for participants to evaluate and analyse multi-year field trials, and evaluate data from existing long-term field trials. One of the ten research associations involved in the BonaRes initiative is CATCHY.

CATCHY has been investigating the use of cover crops as an agricultural measure to preserve soil fertility and ensure yield reliability. Cover crops show different positive impacts on soil health, including the formation of soil organic matter, nutrient availability, protection from erosion and of the formation of soil organic matter for example, and the availability of nutrients in the soil-plant system, but they also provide protection against erosion and help with weed control. The detailed relationships from very small-scale microbiological processes in the soil-plant system, to soil science and plant cultivation aspects and economic efficiency were analysed for various cover crops and cover crop mixtures, and they have been summarised in this brochure along with recommendations for applications in practical agriculture.

We hope you enjoy reading,

Ute Wollschläger on behalf of the BonaRes Centre

Contents

1. Introduction 5
1.1 Definition and objectives of cover crop cultivation 5
1.2 The historical and political context of cover crop cultivation 5
1.3 The CATCHY research project: background, objectives and description 7
2. Strategies for integrating cover crops into crop rotations 11
2.1 Managing crop residues 11
2.2 Choosing crop rotations, crop species and crop varieties 12
2.3 Sowing systems 13
2.4 Cover crop fertilisation 16
2.5 Managing the dying off process 17
3. How can the benefits of multiple crop species be used in cover crop mixtures? 18
4. How cover crops influence soil structure and quality 23
4.1 Soil organic matter formation and carbon in soil 23
4.2 Reduction of leaching losses and nutrient balance 25
4.3 Soil structure and water balance 27
5. Looking beneath the surface: how cover crops shape the rhizosphere 30
5.1 Why is the diversity of the microbial communities in soil so important? 32
5.2 Efficient nitrogen supply through microorganisms 34
6. How cover crops influence nutrient balances 36
6.1 Nutrient uptake 36
6.2 Nutrient conservation 39
6.3 Nutrient transfer 40
7. Effects on main crop yields 46
8. Cover crop cultivation in times of climate change 50
8.1 Establishment strategies 50
8.2 Selecting species 51
8.3 Failed establishment 52
8.4 Effects on yield 53
8.5 Do cover crops cost the main crops water? 53
9. When is cover crop cultivation profitable? 55
9.1 How can the profitability of cover crop cultivation be calculated accurately? 55
9.2 Profitability of cover crop cultivation on typical farms in southern Germany 58
9.3 Potential for increasing profitability by expanding cover crop cultivation 58
9.4 Results 59
9.5 Summary 63
10. Summary and outlook 65
Species directory 68
References 70

1. Introduction

Sophia Breische, Carmen Fiedler,

Jan Hendrik Schulz, Matthias Westerschulte

1.1 DEFINITION AND OBJECTIVES OF COVER CROP CULTIVATION

The cultivation of cover crops refers to the greening of land used for arable farming between the cultivation of two main crops[1]. A range of different crop species can be utilised, either sown alone or in a mixture with various other species. Depending on the farm and crop rotation, these breaks in cultivation can be used solely for soil regeneration or additionally for growing forage.

Fig. 1-1: The main objectives of cover crop cultivation.

Cover crop cultivation has a proven positive influence on the biological, chemical, and physical properties of soil[1] and thus plays a key role in the establishment of a resilient crop production system.

In this context, the activation of soil biology plays a significant role. The interaction between the cover crop and soil organisms lays the foundation for process optimisation in the soil.

Overall, the functions and objectives of cover crop cultivation in arable farming vary and differ depending on the location, farm type and crop rotation. Fig. 1-1 provides an overview.

1.2 THE HISTORICAL AND POLITICAL CONTEXT OF COVER CROP CULTIVATION

The history of cover crop cultivation began when farmers realised that certain species of crops had a positive effect on the development of the crops that they planted afterwards. It all started a few centuries BC, when Cato (234 - 149 B.C.), one of the first agricultural economists, identified lupin (*Lupinus*), field beans (*Vicia faba*) and vetch (*Vicia*) as having a positive impact on the growth of other crops in the crop rotation. Hildegard von Bingen (1098 - 1179) cultivated white lupin (*Lupinus albus*) to improve soil fertility in her garden. The effects of this crop on soil fertility were initially completely forgotten about after her death and were only rediscovered in the 18^{th} century. In

1784, Frederick the Great, the King of Prussia at the time, tried to improve the quality of sandy soils by spreading green manure made from lupin. Agricultural economists Carl von Wulffen and Albrecht Thaer took a similar approach in 1810. Their sandy soils in Northern Germany were not sufficient to ensure the successful growth of the white lupin. In 1840, however, Borchard successfully established the cultivation of the less demanding yellow lupin (*Lupinus luteus*). Two years later, Theodor H. Rimpau returned from his travels and brought with him serradella (*Ornithopus sativus*) to grow as a crop for green manure. The cultivation of yellow lupin and serradella proved to be successful in areas with lighter soils first and then spread further. Ernst Albert Schultz-Lupitz (1831 - 1899) confirmed the nitrogen-accumulating properties of legumes[1].

By the mid-20th century, the cultivation of cover crops for forage production had gained great importance. In particular, red clover (*Trifolium pratense*), alfalfa (*Medicago sativa*) and fodder beet (*Beta vulgaris*) were used to improve the quality of cattle feed. Likewise, the value of legumes as a preceding crop for potatoes *(Solanum tuberosum)* and fodder beet grown in light soils was also recognised. The improvement of soil structure and tilth through the intensive root penetration and the production of soil organic matter by the cover crops became increasingly important over the years[1].

In the 1920s, the "Landsberger mixture", a cover crop and forage mixture made up of a combination of hairy vetch (*Vicia villosa*), Italian ryegrass (*Lolium multiflorum italicum*) and crimson clover (*Trifolium incarnatum*), was developed and had a lasting impact as a crop for green manure and forage cultivation.

Over the years, other species were found to be profitable cover crops for arable farming, too.

Fig. 1-2: Landsberger mixture.

As a result, grass-clover ley, oil radish (*Raphanus sativus var. oleiformis*), Italian ryegrass (*Lolium multiflorum*) and phacelia (*Phacelia tanacetifolia*) were all increasingly integrated into cultivation systems.

During the "Green Revolution" and with the growing use of synthetic plant protection products and fertilisers after the Second World War, crop rotations were slimmed down[4]. Grasses dominated arable forage production, and from 1960 onwards the production of silo and grain maize for forage production [4] on German fields increased. The MacSherry Reform, which was introduced in 1992, reduced price support for agricultural products[5]. As a result, farmers started to focus their production on high-yield crops that are mostly harvested late (such as fodder beet). This reduced the cultivation of cover crops that require an earlier sowing window[4]. At the turn of the millennium, cover crops once again grew in importance. The Common Agricultural Policy (CAP) reforms in 2003 and the introduction of Cross Compliance brought with them new requirements for farmers with regards to the receipt of direct payments[5]. Environmentally friendly and biodiversity-promoting measures were focused, as did the consideration of cover crops as a means of meeting environmental policy goals.

Another important political milestone for cover crop cultivation was the agricultural reform in 2014. This marked the linking of direct payments to the Greening measures that came into force from 2015 onwards. An important condition for receiving the greening bonus was the designation of ecological focus areas (EFAs), which include areas set aside for cover crops[4]. In addition, the cultivation of simple cover crop mixtures, which usually consist of two different species of crops, can be financially supported by budgets for measures that promote agri-environmental areas. As a result, cover crop cultivation gained a new, primarily financial, relevance. The amount of agricultural land used to cultivate cover crops increased significantly with the implementation of the EU Greening measures. The funding programme came to an end with the reframing of the CAP on the 1st of January 2023.[6]

The CAP 2023 and the Farm to Fork Strategy are crucial EU agro-political measures that have grown from the European Green Deal. The aim of the Green Deal is to create a resource-efficient and competitive economy that does not promote climate change and negative environmental effects any further. As part of the deal, all EU member states are obligated to be climate neutral by 2050 and reduce their CO_2 emissions by at least 55 % by 2030. In May 2020, as part of the conception of a new CAP, the Farm to Fork strategy was introduced as a corner stone of the European Green Deal. This strategy should pave the way for healthier and more sustainable food in Europe and assist Europe to achieve climate neutrality by 2050. Alongside the increase in areas used for organic farming, the improvement of animal welfare and reduction of food losses, halving the amount of plant protection products used, and reducing fertiliser use by at least 20 % are the major objectives of the Farm to Fork strategy. Thus, other measures will have to be taken in the long term in order to secure the nutrition and health of crop stands. Cover crops can make a significant contribution to this as they show nutrient-conserving and phytosanitary effect.

Overall, the CAP 2023 should support smaller agricultural business and help fulfil the European Union's climate and environmental objectives. Individual EU member states can design their own specific measures in accordance with higher-level regulations. In Germany for example,, the payment of the basic premium to farmers is tied to compliance with the new standards for the good agricultural and environmental condition of land (GAEC), among other things. When it comes to cover crop cultivation, the crop rotation design and soil coverage over winter is very important. With the GAEC standards, there are additional obligations that must also be observed.[108]

As a result, despite the cancellation of the greening bonus, the CAP 2023 and Farm to Fork Strategy install a renewed need for cover crop cultivation. With the continuing reduction in the use of plant protection products and fertilisers, it is now important to optimise crop production systems by means of an intelligent expansion of crop rotations as part of integrated crop production. Cover crops can make a significant contribution[6].

1.3 THE CATCHY RESEARCH PROJECT: BACKGROUND, OBJECTIVES AND DESCRIPTION

In view of the environmental, social, and economic challenges facing the agricultural sector, it is crucial that farmers fully exploit the potential of cover crop cultivation for an integrated, sustainable crop production. Here, it is obligate to fully understand the many positive effects of cover crop cultivation. Extensive research is needed to get to this point, particularly with regards to the measurability of soil parameters to describe the biological, physical, and chemical effects of cover crops within the crop rotation. There is a variety of new technical methods that can be used to investigate the effects of different species of crops either individually or when mixed with others. The CATCHY research project ("Catch crops as agronomic means to ensure sustainable soil fertility and yield security") makes use of these scientific approaches. It was conducted from 2015 to 2024 as part of the BonaRes ("Soil as a sustainable resource for the bioeconomy") funding initiative, which is supported by the German Federal Ministry for Education and Research (BMBF), and had the following objectives:

1. To establish long-term field trials to evaluate different crop rotations, and more specifically various cover crop mixtures.
2. To evaluate the effect of individual species and mixtures of cover crops on crop yields, agronomic characteristics, and soil parameters, like the size and availability of nutrient pools, nutrient flows, carbon inputs in the soils, soil structure, and the functions and diversity of crop-related and soil microorganisms.
3. To understand the importance of root functions when it comes to the nutrient uptake of crops and their interactions with microbial communities in the soil and to improve this.
4. To contribute to the establishment of improved management concepts to encourage soil fertility, maintain yield capacity and stabilise the agroecosystem.
5. To conduct an economic evaluation of the long-term effects of cover crop cultivation.

To achieve these objectives, a long-term trial was designed during which a crop rotation with winter wheat *(Triticum aestivum)* - cover crop - maize *(Zea mays)* was cultivated continuously over a period of nine years. White mustard *(Sinapis alba)*, phacelia, bristle oat *(Avena strigosa)* and Egyptian clover *(Trifolium alexandrinum)* were used as cover crops, either in pure stands or in a four-crop mixture. A 12-crop mixture, TerraLife® Maize-Pro, was also included in the trial. Parcels of land where no (cf. Tab. 1-1) cover crops were sown (fallow) were used as a control. The trial sites were located in Asendorf (district of Diepholz, Lower Saxony) and Triesdorf (district of Ansbach, Bavaria). The crop rotations were staggered, with one starting in 2015 and the other in 2016, to ensure that each year the cover crops and the main crops of maize and wheat (Blocks 1 and 2 in Fig. 1-4) could be observed at the same time.

Fig. 1-3: Sites of the CATCHY trials in Germany. (red)

During a second long-term trial conducted at the same time (Blocks 3 and 4 in Fig. 1-4), the impact of crop rotation diversification on soil parameters and crop yield was examined through the integration of field beans as another main crop.

Fig. 1-4: Aerial view of the field trial in Asendorf (52.76335 N, 9.02475 E). The area in the red rectangle marks the entire trial area. The blocks for the different starting points of the two crop rotations are marked with the blue rectangles and numbers. Blocks 1 and 2 are the same Leg- crop rotation planted one year apart. The same goes for Blocks 3 and 4 of the Leg+ crop rotation (Image from autumn 2021, downloaded from https://opengeodata.lgln.niedersachsen.de/#dop).

This crop rotation was set up in the same way as the winter wheat - cover crop - maize rotation, but with every second cycle the maize was replaced with field beans, resulting in a repeating sequence of winter wheat - cover crop - maize - winter wheat - cover crop - field beans. The same cover crops were used in both trials. Hereinafter, the first crop rotation will be referred to as “Leg-”, and the second as “Leg+”. In further field trials conducted at both sites, other species were evaluated to see if they were suitable for use as cover crops and systematically combined into mixtures. These trials were integrated into the usual crop rotations and therefore changed locations every year. In the following year, maize was cultivated on the parcels to investigate the effects of the cover crop on yields.

The average annual temperatures at the sites in Triesdorf and Asendorf are 9.1°C and 9.3°C. The average annual precipitation in Triesdorf is 686 mm and 751 mm in Asendorf. During the years that the trial took place, between 2015 and 2022, the average rainfall was 595 mm in Triesdorf and 790 mm in Asendorf. The soil in Triesdorf is a pseudogleyed earth with a wide variety of textures, ranging from sandy (S) to silty loam (SiL) (Average values: clay 16 %, sand 50 %, silt 45 %). The average soil organic matter content in the topsoil is 2.4 % (1.4 % C_{org}) and the pH values are 7.4 on average. In Asendorf, the soil consists of gley-like luvisol from a shallow loess layer on top of glaciofluvial sands. As such, the soil texture on the site is loamy silt (average values: clay 8 %, sand 19 %, silt 73 %) with an average soil organic matter content of 3.0 % (1.7 % C_{org}) and pH values around 6.5. A decisive factor when it comes to the effects of cover crop cultivation, is the agronomic management of cover crops. To get accurate but still realistic results, the trials were managed as described below. The soil cultivation was carried out exclusively in conservation tillage and to a depth of up to 20 cm depending on the soil structure. The deeper loosening of the soils was done as needed before the winter wheat and cover crop was sown. Before the summer crop was sown, a primarily shallow tilling was carried out so that the cover crop residue could be chopped up and incorporated into the soil. If there was insufficient frost over winter, the cover crop was killed off with a total herbicide and then shredded a mulcher if needed. The crops were sown with standard equipment, namely precision seed drills for the maize and double disc seed drills for all other crops. The crop protection was done with chemical-synthetic substances in accordance with the legal requirements. The fertilisation with essential nutrients (P, K, Mg, S) was applied to the main

crops and corresponded to the amount of the average removals of the respective crops at the respective sites. The amount of nitrogen fertiliser applied was based on the applicable German Fertiliser Act (GFA).
In order to make the potential effects of the nutrients more visible, the nitrogen fertiliser requirements, which are based on the values for Nitrate Vulnerable Zones (NVZs) laid out in the German Fertiliser Act (GFA), were reduced by 20 % for the main crops.
With maize, an additional 40 kg of nitrogen was removed from the nitrogen supply for the cover crops. The fertilisation was purely mineral and the same for all trial crops. The harvest residues were not removed.

Fig. 1-5: Image of the field trial in Asendorf (taken on 12th October 2017, Dörte Schweneker).

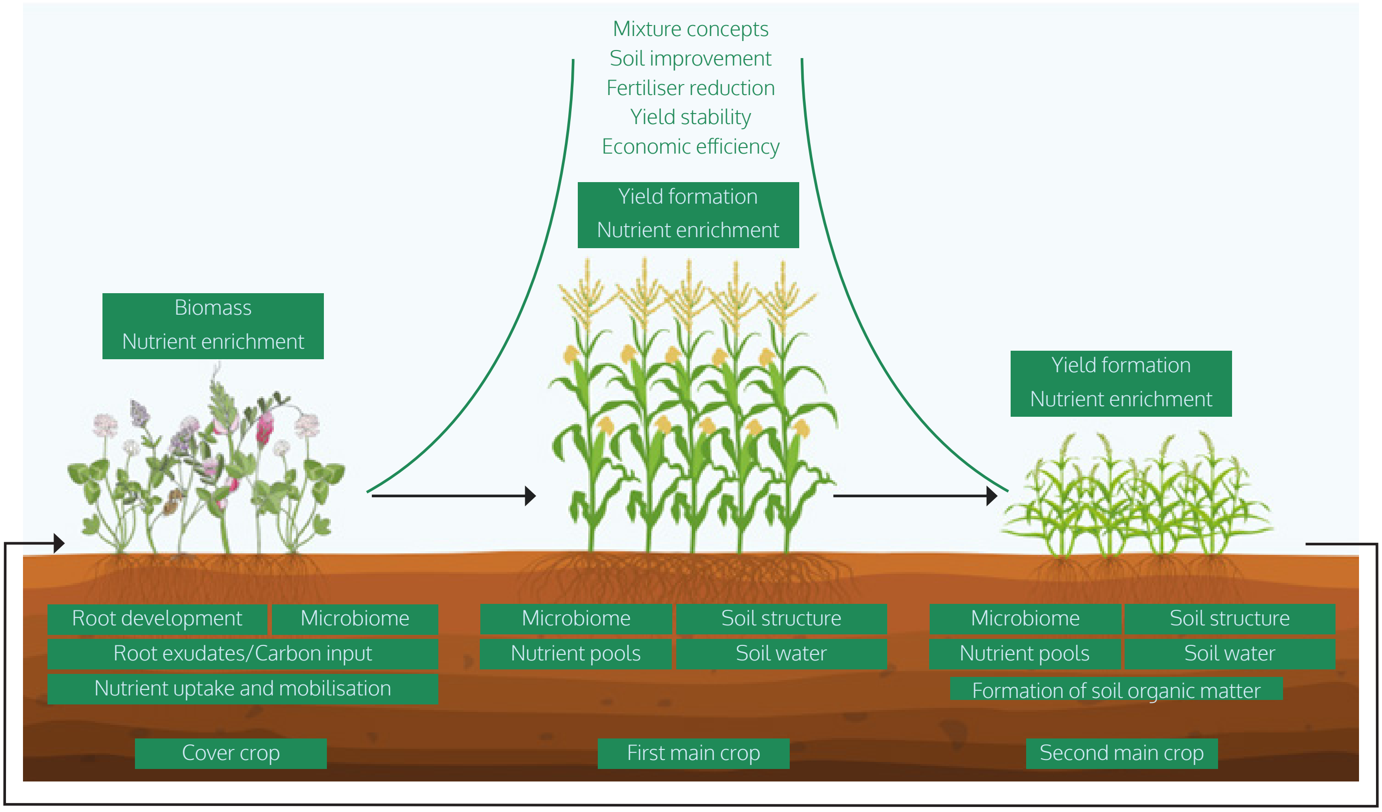


Fig. 1-6: Schematic representation of the structure and research focuses of the CATCHY project. Plant diagram according to Kutschera.[7]

The seeding rate of the cover crops is based on the recommendations from RENIUS for the sowing of white mustard 18 kg/ha^{-1}, phacelia 12 kg/ha^{-1}, bristle oat 100 kg/ha^{-1} and Egyptian clover 25 kg/ha^{-1} on their own. The contents of both mixtures can be found in Tab. 1-1.
This brochure presents the results from the trials conducted as part of this project and puts them into the context of the results taken from literature. It provides a comprehensive insight into the current state of research on the influence of cover crops on soil and microbial functions, on nutrient management, on the yield formation of main crops, and on the sustainability of crop rotations.

Fig. 1-7: In the CATCHY project, the cover crop mixture TerraLife® MaizePro was trialled as a biodiverse mixture with twelve different species of crops (12-crop mixture).

Tab. 1-1: Composition of the trialled mixtures.

MIXTURE	SPECIES	BOT. NAME	PROPORTIONAL WEIGHT (%)	SEEDING RATE (KG/HA)
12er crop mixture (TerraLife® Maize Pro)	Field pea	*Pisum sativum*	38	35
	Sorghum	*Sorghum bicolor*	14	
	Phacelia	*Phacelia tanacetifolia*	7	
	Flax	*Linum usitatissimum*	8	
	Hungarian vetch	*Vicia pannonica*	6	
	Radish	*Raphanus sativus*	5	
	Niger	*Guizotia abyssinica*	4	
	Sunflower	*Helianthus annuus*	2	
	Camelina	*Camelina sativa*	2	
	Persian clover	*Trifolium resupinatum*	4	
	Alsike clover	*Trifolium hybridum*	5	
	Crimson clover	*Trifolium incarnatum*	5	
4-crop mixture	White mustard	*Sinapis alba*	16	25
	Phacelia	*Phacelia tanacetifolia*	20	
	Bristle oat	*Avena strigosa*	36	
	Egyptian clover	*Trifolium alexandrinum*	28	

2. Strategies for integrating cover crops into crop rotations

Sophia Breische, Carmen Fiedler,

Jan Hendrik Schulz, Matthias Westerschulte

The success of a cover crop largely depends on having a well-developed stand. The right management strategy covers everything from the selection of the preceding crop and the corresponding cover crop, to the seeding equipment used and the preparation of the seedbed for the subsequent crop.

2.1 MANAGING CROP RESIDUES

Before harvesting the preceding crop, there are aspects that must be taken into consideration for the establishment of the cover crop. Depending on the preceding crop, various types and amounts of organic matter can remain on the surface, distributed in different ways. This can impact the establishment of the cover crop in several ways. For example, if the preceding crops have been threshed, the straw can be cleared or left on the fields. To guarantee the emergence of a cover crop, several different points must be regarded:

- The fine chopping of crop and straw residue reduces mechanical resistance for cover crop seedlings[17].
- A homogeneous distribution of the crop residues encourages an even field emergence. The type and amount of crop residues determines the sowing equipment used. For example, if the layer of straw left on the field is too thick, this can block the seed drill.
- The type and amount of crop residues also has a decisive impact on the nutrient dynamic of the soil. For example, cereal straw has a very high C:N ratio and so if it is incorporated into the soil it can significantly restrict the availability of nitrogen in the soil for the cover crop[4].
- When handling crop residues before the cover crop is established, the site-specific soil condition and weather conditions at the time must always be taken into account.
- Covering the surface of the soil with crop residue protects it against water evaporation, silting and erosion.

In addition, the failure and growth behaviour of the preceding crop has a decisive influence when it comes to preparing the seedbed and choosing the cover crop. In particular, barley *(Hordeum vulgare)* and rye *(Secale cereale)* can grow through cover crop stands[8]. As such, in crop rotations like this, it is important to adapt the tilling accordingly and to select highly competitive cover crops that establish themselves quickly and deprive the volunteer cereals of light, water, and nutrients.

2.2 CHOOSING CROP ROTATIONS, CROP SPECIES AND CROP VARIETIES

POSITIONING IN THE CROP ROTATION

In order to get the best results possible out of the cover crop, it is important to select the best position for it in the crop rotation. Various parameters should be considered:

- Vegetation period and weather conditions
  For an optimal establishment, the cover crop must be planted at the right time to ensure sufficient growth[14]. The more time the crop has for vegetative growth, the more biomass it can form and thus exert its varied and positive effects. The rule "One day of growth for a cover crop in July equates to a week of growth in August and a month of growth in September" has proven to be true[9]. With a later sowing, there is a risk of an uneven and in some places a complete failure of field emergence depending on the variety of cover crop chosen. The species that can tolerate an early or late sowing are detailed in the subchapter "Choosing species and varieties". In view of the increasingly drier and warmer summers, cover crops that can withstand high temperatures and need less water should be selected. One example of such a crop is Sudan grass *(Sorghum sudanense)*.
- Subsequent crop requirements
  The subsequent crop also influences the choice of cover crop. For example, if during the following spring fodder beet is to be planted after mulch seeding, the previously planted cover crop should leave behind a fine, not too rich biomass[8]. For an ideal seedbed in this case, the cover crop should form little lignin (e.g. legumes like field peas or hairy vetch) to ensure that the crop residues can be easily worked into the soil. Certain cover crop species reach the seed ripening stage quicker than others and so can cause growth problems in the subsequent crop. One example of this is Tartary buckwheat *(Fagopyrum tataricum)*, a Polygonaceae that is difficult to control, particularly in fodder beet stands.
- Phytosanitary precautions
  To prevent disease in subsequent crops, cultivation breaks must be implemented for many main crops. Of course, this also has an effect on the choice of cover crop. Plant species that encourage the development of specific disease-causing pathogens in the main crops should either not be used at all or only used to a limited extent. For oilseed rape cultivation *(Brassica napus)*, a three- or four-year break in the cultivation can help here. It counteracts the spread of pathogens that trigger diseases like clubroot or verticillium[10]. Many crop pathogens do not only affect oilseed rape but other crucifers too. As such, they must be given special consideration when it comes to choosing the cover crop for a crop rotation. Even small amounts of crops like mustard, tillage radish *(Raphanus sativus)* or camelina *(Camelina sativa)* can encourage the spread of clubroot. Legumes, however, like Egyptian clover and Persian clover *(Trifolium resupinatum)* can prevent the propagation of clubroot pathogens[9]. If there are legumes like field beans, lupins, or field peas *(Pisum sativum)* as a main crop in the crop rotation, the proportion of legumes in the cover crop mixture must be adapted accordingly. Depending on the legume, a cultivation break lasting several years may need to be considered to prevent yield losses caused by legume fatigue[9].

THE SOWING DATE DETERMINES THE SPECIES CHOSEN

The timeframe for planting the preceding crop determines the species or mixture of cover crops chosen. It also determines the remaining vegetation period or the time until the next main crop is sown. During this time, it is important to achieve the highest photosynthesis rate possible with a well-established stand and an associated high leaf index, as this increases the excretion of root exudates accordingly. At the same time, the development of volunteer seeds by the cover crop is to be prevented. Thus the speed and duration of vegetative and generative growth are to be estimated correctly. Correspondingly, main crops that are harvested early (e.g. winter barley) should be combined with species and varieties of cover crops that have as late a generative phase as possible (e.g. niger, Abyssinian cabbage). With main crops that are harvested later (e.g. winter wheat), cover crops that have a quicker vegetative and mostly earlier generative phase (e.g. oil radish, Tartary buckwheat) should be preferred. More detailed information about the sowing times of individual cover crops can be found in Kivelitz (2017)[9] and Lütke-Entrup et al. (2018)[4]. In particular, if a cover crop is intended to be used as forage planned in the form of a cut or meadow (e.g. mob grazing) then the sowing time and crop species used must be coordinated accordingly. This is the only way to establish a qualitatively and quantitatively usable stand of plants. Selecting cover crops that grow well is in this case obligate. Annual ryegrass, for example, is especially suitable, as they are able to form usable biomass far quicker than the comparatively slower Italian ryegrass.

Fig. 2-1: Example of a varied cover crop mixture.

2.3 SOWING SYSTEMS

When it comes to choosing a sowing system, it is important to differentiate between fine- and coarse-grained species of crops. Many cover crop varieties, like Persian or Egyptian clover, have fine seeds and quire shallow planting depth of one to two centimetres[11]. Legumes, which have larger seeds, should be planted deeper depending on how they germinate. Lupin spaces have epigeal (aboveground) germination and thus need to be planted at a depth of between two and four centimetres. Field peas, field beans, and vetch, however, have hypogeal (underground) germination and so must be planted at a depth of at least four or five centimetres to ensure an ideal establishment[4]. To avoid multiple work processes and passes, a compromise must be found when tilling fields with a diverse cover crop mixture. For most mixtures, a sowing depth of 2-3 cm maximum is recommended.

The aim is to ensure that the seeds have sufficient soil contact and water to achieve an even field emergence and a rapid development of the young plants[11]. The specific field conditions and the requirements of the chosen cover crop must always be considered. Under dry conditions, rolling can help to ensure a successful germination. However, the soil must remain open to ensure soil respiration. Traditionally, a distinction is made between three different sowing systems:

- Blank sowing
- Mulch and stubble sowing
- Direct sowing

BLANK SOWING

With this sowing technique, straw and crop residues are incorporated deeply into the soil during the tilling after the preceding crop has been harvested[4]. Usually, ploughing takes place this way, the cover crop gets a fresh seedbed.

The topsoils must be reconsolidated after ploughing, particularly with lighter soils. The machinery used must be selected based on the predominant soil conditions.

EQUIPMENT USED FOR BLANK SOWING

Seed drills used on plough furrows create the best conditions for an even spreading of the cover crop seeds. Without the residues from the preceding crop, the drill ploughshares can penetrate the soil more easily and plant the seeds precisely[8]. This ensures that all seeds are evenly covered with soil, encouraging an even field emergence. Due to the low area performance when ploughing and the comparably high energy costs, many farms have stopped using blank sowing for cover crops in recent years[9].

Tab. 2-1: Advantages and disadvantages of blank sowing (information compiled from various sources).[4,11-14]

ADVANTAGES	DISADVANTAGES
• Minimal competition from weeds and volunteer cereals • The removal of crop residues from the soil surface makes it easier to plant seeds evenly • The "green bridge" for crop pathogens like aphids or phoma is broken • Cover crops with particularly fine seeds can establish well in blank sowing • Deep loosening of the soil is stabilised again by the cover crop	• Soil is not protected against evaporation and there is a high risk of erosion due to a lack of organic matter • Impacts the performance of soil organisms due to missing mulch layer and intensive tilling • Intensive intervention in the soil structure can result in plough sole compaction • Limited combination of work processes • Low area output and high energy costs

MULCH AND STUBBLE SOWING

This sowing technique describes a shallow to deep non-turning tilling and subsequent sowing of the seeds in the topsoil that the crop residues have been mixed into. The process has been shown to reduce the soil drying out and the loss of soil organic matter, while increasing area outputs. Depending on the weed management strategy used, there may be one or several cultivation steps necessary before the cover crop can be sown.

Fig. 2-2: Cover crop sowing during the shallow tilling (DSV 2015).

EQUIPMENT USED FOR MULCH SOWING

On areas with a layer of crop residues, seed drills can be used. The precision of the seed placement depends on how evenly and intensively straw and other organic matter is worked into the soil[9]. To save time and money, the cover crop can also be planted with a pneumatic spreader mounted on a cultivator or disc harrow. This ensures that the seeds are distributed over a wide area via a unit or hose either in front of or inside a packer roller[9].
A particularly simple and affordable sowing technique is the wide spreading of the seeds with a fertiliser spreader. However, there is a risk of uneven field emergence with this approach. And dark germinators and cover crop varieties that need to be planted at a certain depth cannot germinate. During periods of drought, this technique can result in a significantly delayed germination (approx. 7 - 14 days) compared to drill sowing. It can be helpful to increase the seed rate by up to 20 % depending on the sowing conditions (reconsolidation, tilth, and moisture content of the soil)[9].

Tab. 2-2: Advantages and disadvantages of mulch and stubble sowing (information compiled from various sources).[11-14]

ADVANTAGES	DISADVANTAGES
• Protection against erosion and evaporation • Reduced tilling encourages soil life and preserves soil structure • The combination of tillage and spreading equipment reduces the number of passes necessary • Higher area output	• Risk of insufficient planting precision for certain crops • Risk of uneven field emergence • Facilitates the survival of crop pathogens • Competition from quick-growing volunteer cereals • Tilling can result in water losses

DIRECT SOWING

This technique includes the tilling of the soil post-harvest. The residues from the preceding crop are mechanically chopped up. Afterwards, the cover crop is sown directly into the straw or stubble of the threshed crop[14]. This approach helps to conserve water and reduce the germination of weeds and unwanted grasses.

EQUIPMENT USED FOR DIRECT SOWING

Direct sowing has the highest requirements in terms of equipment. It is important to think about the flow of crop residues, particularly with larger amounts of straw, the degree of precision when planting the seeds, the filling in of furrows, and the soil closure. In practice, specially developed direct sowing machines, like disc or tine seed drills have proven to be particularly effective. Still, the farm-specific machinery also has to be taken into account. Direct sowing should be done as soon as possible after the harvest of the preceding crop. This way, the cover crop gets the longest vegetation period possible. In addition, by minimising evaporation, an optimal use of water reserves is ensured. Furthermore, when cover crops are sown immediately after the main crop is harvested, they can establish themselves quickly and so minimise the emergence rates of weeds and volunteer cereals. There is, however, a slightly higher risk of an uneven field emergence when cover crops are planted in soils with straw or stubble residues.

Tab. 2-3: Advantages and disadvantages of direct sowing (information compiled from various sources)[4,14,15].

ADVANTAGES	DISADVANTAGES
• A lower rollover frequency and an improved load-bearing capacity reduce the risk of compaction • Reduced risk of erosion and evaporation • Encouragement of soil life and formation of soil organic matter due to a lack of tilling and due to biomass being left on the soil surface • Rapid suppression of emerging volunteer cereals • Suppression of light-germinating weeds as there is no tilling	• Possible survival of plant pathogens and weeds • Strict requirements with regards to the equipment and sowing time, therefore high risk of insufficient soil closure and uneven field emergence (particularly with large seeds) • Risk of mouse and snail damage

ALTERNATIVE SOWING TECHNIQUES

UNDERSOWING

Undersowing has been proven to guarantee a seamless transition from the main crop to the cover crop. Until now, various clover or grass species or mixtures have mainly been sown in existing main crop stands. The species selected, fertiliser and herbicide use, have a significant influence on the development of cover crops that have been undersown[11]. When selecting a crop to undersow, it is important to choose one that can survive the crop cultivation measures carried out on the main crop but not compete with it.

Fig. 2-3: Undersowing can be used to green areas once the main crop (here maize) has been harvested (DSV 2014).

A finger weeder or a hoe with a mounted seed box or pneumatic spreader has proven to be effective when establishing an undersown crop. Depending on the location and weather conditions, undersown crops can also be planted without being incorporated into the soil. The time at which the undersown crop is introduced is highly dependent on the main crop and the selected undersown crop species. This technique has proved to be particularly effective in maize cultivation. Here for example, slower growing red fescue can be sown at the same time as the maize crops, but it is best to plant perennial or Italian ryegrass when the maize crops reach the 6- to 8-leaf stage. Thanks to this technique, the short vegetation period after the maize is harvested can be effectively covered by a cover crop.

COMBINE HARVESTER SOWING

To reduce the rollover frequency on the field and limit work peaks, seeding implements can be attached directly to harvesting machines. Similar to undersowing, combine harvester sowing helps cover crops to make better use of the vegetation period. When it comes to the equipment, either a direct seeding unit or a spreading seed tank can be mounted on the combine used. The last option is easier and cheaper to implement, but it can only be used to spread seeds on stubble. Trials conducted by the Nürtingen-Geislingen University / Hochschule für Wirtschaft und Umwelt Nürtingen-Geislingen (HfWU) in 2008 and 2009, showed that mustard sown with a combine harvester on areas with a straw layer did not produce results that were any worse than if it had been sown directly or with a cultivator. This confirms the assumption that the establishment of cover crops as close as possible to the harvesting of the previous crop results in faster soil coverage[16]. One disadvantage of this approach, however, is that combine harvesting requires greater amounts of energy and time.

DRONE SOWING

Another option is to use a drone to sow the cover crop before the preceding crop is harvested. Similar to undersowing, this technique means that the arable land can be covered even quicker after the harvest, thus reducing fallow periods. It also helps to extend the vegetation period of the cover crop stand. In comparison to conventional cover crop sowing with tractors and seed drills, this extension of the extra vegetation period can result in a quicker establishment of the cover crop. This in turn can lead to 25 % more coverage just four weeks after the main crop has been harvested, meaning that the various advantages that the cover crop offers can be utilised earlier. In addition to the time saving, another significant advantage of drone sowing is that it reduces the rollover frequency and soil structure damage[106]. The risk of this technique is that the seeds can only be spread on top of the soil and are not incorporated into the soil, thus it is impossible to guarantee ideal soil contact. However, this risk is counteracted by the fact that the seeds are shaded by the dying main crop in the beginning and are then covered with further plant residues after the harvest. This encourages the creation of a favourable microclimate. At this point, cover crop mixtures that contain several different species have proven to be effective when sown with a drone. This way, the individual species can compensate for each other depending on the weather conditions. Based on initial findings from trials using this technique, there is no need to increase the seeding rate[106]. Schmidt confirms that cover crop mixtures, like the TerraLife® MaizePro DT for example, produce very good field emergence results when planted at the recommended seeding rate[106]. In addition to the points mentioned above, drone sowing is significantly cheaper and faster than using a tractor for tilling and sowing. Overall, drone sowing will gain more importance in the future[106].

2.4 COVER CROP FERTILISATION

It is very challenging to describe the nutrient dynamic in cover crop stands as it depends on a wide range of different parameters. This can include the soil type and quality, the nutrient supply potential, the water supply, the species composition, the sowing conditions, and the development stage of the cover crop[107]. In particular, the objective with regards to the subsequent crop and a possible use of the cover crop, but also the nutrient supply provided by the preceding crop define the possible nutrient requirements. The specifications of the German Fertiliser Act (GFA) and the conditions in the respective area determine whether fertiliser can be applied. As such, the fertilisation must always be done on an individual basis and within the framework of good professional practice. The biomass formation of the cover crop is largely controlled by the nitrogen supply. To encourage the development of the young crops, a starting dose of between 30 and 60 kg N/ha has proven to be effective for crops with high nitrogen requirements, like oil radish and white mustard, depending on the location and prevailing C:N ratio[4]. An undersupply of nitrogen can result in insufficiently developed stands which can then only fulfil their functions to a limited extent. It is important to remember that legumes do not require an additional nitrogen fertilisation. Likewise, soils with a high nitrogen supply and a good structure ensure a good cover crop emergence without any additional nitrogen.

Straw management also has a major influence on the cover crop nutrient supply. In this regard, it is important to ensure that the straw left behind when the preceding crop is harvested is finely chopped and evenly spread on the surface. The blades on the chopper used for this must be in good condition and a chaff spreader is a recommended option for spreading the swath. Incorporating the straw into the soil, stimulates nutrient mineralisation and chaff decomposition. Here, the harvest residue should not be worked in too deeply. Using a plough can result in the formation of a straw mat in the subsoil, which can have a negative impact on the soil's nutrient dynamics (due to decomposition, amongst other things). It is also very important to consider the high C:N ratio of lignified crop residues, which is usually between 40:1 and 80:1. Cereal straw alone contains just 0.5 % nitrogen and has a C:N ratio of around 80:1. As such, the crop residues are not the immediate source of nitrogen for the cover crop itself, but for the microorganisms that break down the straw and stubble. With high C:N ratios over 25:1, a temporary microbial nitrogen barrier forms in the soil. The forms of nitrogen available to crops, ammonium (NH_4^+) and nitrate (NO_3^-), only begin to arise as the decomposition progresses. With no additional nitrogen supply or a supply from the soil, cover crops can suffer from a lack of nitrogen while the straw is decomposing. If nitrogen cannot be added for legal reasons, removing the straw may be helpful. In any case, with cover crop fertilisation the legal framework that applies the respective cultivation area must be observed. For more specific information about fertiliser planning, it is best to refer to official advice.

2.5 MANAGING THE TERMINATION

The management of the dying off process of the cover crop has a significant influence on the development of the subsequent crop. Here, a differentiation must be made between frost-sensitive and winter-hardy cover crops.

Frost can induce the dying off process of frost-susceptible cover crops. But the rotting and decomposition of the cover crop is of vital importance to the mineralisation of the nutrients[18]. Depending on the location and annual weather conditions, mechanically treating plants with a roller can have a supportive effect. For example, breaking off the crop stems can encourage the death of the crop stand. Rolling frozen ground can help to protect the soil from compacting during the wet winter months. And supporting the dying off process can help manage the release of nutrients based on the needs of the subsequent crop. Machines like mulchers or rotary cultivators intensively chop the crops and can release much plant juice, resulting in nutrient losses. Tilling machines, like disc harrows or cultivators, should only be used shortly before the seedbeds are being prepared for the subsequent crop to ensure soil coverage for as long as possible over the winter months. Here, legal deadlines must be complied with. Mechanical soil and plant treatment supports nutrient mineralisation even further[18]. The type and structure of the soil and the sowing system used for the subsequent main crop determine the choice of machinery and the loosening depth.

The vegetation period of winter-hardy cover crops can last until spring and beyond. As a result, these cover crops can exert increased competitive pressure on the subsequent main crop. As such, the cover crop stand must be reduced before the subsequent crop establishes itself. This can be done mechanically, chemically or through grazing and cutting.

Overall, it must be noted that there is a high degree of variability in the positioning of cover crops within a crop rotation. Each individual farm must make decisions based on their location, crop rotations and machinery.

Fig. 2-4: Rolling a cover crop stand during frost.

3. How can the benefits of multiple crop species be used in cover crop mixtures?

Robin Kümmerer

The cultivation of cover crops pursues a range of agronomic, environmental, and societal objectives. The previous chapters described how different the properties of the various crop species that can be used as cover crops are. In order to expand the functions of cover crops and increase their stability, the combination of different species with different properties in cover crop mixtures is recommended and regularly implemented in practice[19,20].
Cover crop mixtures that contain a wide variety of species first came into focus at the beginning of the 2000s, but they found their way into widespread practice with the CAP 2013 and the concept of ecological focus areas. The spectrum of species diversity in cultivated cover crop mixtures ranges from 2 species, which meets the applicable "greening" guidelines, to over 10 different species, in keeping with the idea "the more diverse, the better". Agricultural policies encourage species diversity in cover crop mixtures through specifications like "greening", but also through direct payments for the usage of varied cover crop mixtures, as is the case with programmes in certain German Federal States. While the benefits of cover crop cultivation are already well documented in scientific literature, they have not yet been clearly and unambiguously defined for the cultivation of different mixtures with different species of crops in particular[21].
The idea that the species diversity improves the functions of cover crops is rooted in ecological theories. These state that due to their different requirements when it comes to growth factors like nutrients, water, light and heat and their different capacities to adapt to the growth factors provided, species complement each other and make better use of existing resources than a single type of crop sown alone does. The resulting increased nutrient uptake improves the growth of the cover crops. Due to the higher inputs of nutrients and organic substances in the soils, the soil biology is usually also stimulated[23,109,110,111]. As different crop species have developed different strategies to compete with others while carving out their own niche, the weed suppressing power of cover crops can also benefit from this species diversity[24,112-115]. Different, species-specific

environmental requirements should increase the probability that at least one species can establish itself under the prevailing conditions[25,116-118]. The positive effects of cultivating species-rich cover crop mixtures should lead not only to a better performance of the cover crop but also to increased yields from the subsequent crop. However, according to the results of the CATCHY project and other studies, these high expectations of species-rich cover crop mixtures are not always met. With the shoot biomass of mixtures, a statistically proven synergy effect was only seen in a few cases when compared to cover crops sown alone. This effect was seen more frequently with mixtures of legumes and non-legumes rather than with mixtures of non-legumes alone. In some cases, an optimisation of the mixture composition helped to improve the biomass output of cover crop mixtures. Although the above-ground biomass performance is related to many important functions of a cover crop, it is not the only evaluation criteria for the overall performance. Further important aspects, like the root performance of different cover crops and their effects on the nutrient balance or the microbiome in the soils are covered in the following chapters.

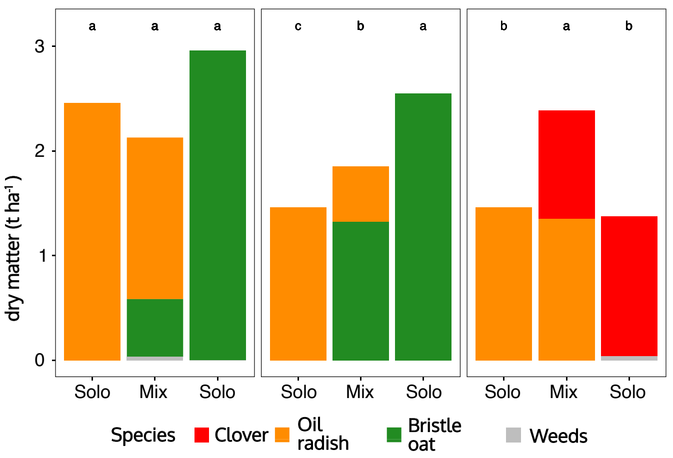


Fig. 3-1: Examples of dry matter yields from shoots of various species of crops sown alone and two-crop mixtures from different years and sites. The combination of two species to make a cover crop mixture can have an antagonistic (left), and additive (centre) or a synergistic (right) effect. Different letters indicate significant differences.

The expectations arising from ecological theories here were not always met. This may be due to the fact that these theories are mainly based on natural or grassland ecosystems that only experience minor or even no at all, unlike arable farming systems, and are therefore subject to natural succession[27]. As a general rule, in arable farming systems the crop grown and the tilling, fertilising and care measures all change every year. The growth period of cover crops is often limited to just a few weeks making it difficult to compare cover crops grown on arable farms with findings from natural ecosystems. Compared to natural ecosystems, with the cultivation of cover crops in intensively farmed arable systems there are often no nutrient limitations as after the main crop is harvested there is an excess of nutrients, a high soil mineralisation potential or the soil is fertilised with farm manure. In fact, these high amounts of nutrients frequently exceed the uptake capacities of the cover crops. The nutrient uptake capacities of cover crops can also be limited by other factors like a low availability of water or a vegetation period that is too short. The results of our field trials show that the cultivation of cover crop mixtures under the conditions mentioned above brings fewer benefits than cover crop mixtures grown under nutrient-restricted conditions, such as those that prevail in natural ecosystems. In practice, cover crops often have limited nutrient supplies due to restrictions enforced by fertiliser laws, during periods of drought or when they are cultivated on marginal locations.

Some of the disadvantages of cover crop mixtures include higher seed costs, increased demands on sowing equipment due to the different seed sizes and higher management requirements due to the different optimal sowing times or behaviour of the different species in the mixture when subject to frost, for example. Species-rich mixtures are therefore not inherently more suitable for cover crop cultivation than pure seed. Nevertheless, there are good reasons to favour cover crop mixtures over pure seeds. Cover crops should always been grown as a mixture of different species if this fulfils the required functions better than just one species planted on its own, and if the advantages of planting a mixture outweigh the disadvantages. In order for this to work, there are a few points that must be considered from a cultivation perspective.

First, species are adapted to locations in different ways and therefore a cover crop mixture that functions at one location may not work at another. In addition, crops that grow together in a community interact with each other. For keen growers, the first thought that will come to mind is that the crops will end up competing for nutrients, light, and water. In stands consisting of just one species of crop, this type of interaction is relatively easy to calculate as long as roughly equal conditions were provided for all plants in the stand. By choosing the right seeding rate, a crop density can be established for each location that represents an optimal ratio between individual plant yield and competition, thus maximising the overall yield of a crop. In cover crop mixtures, this is not so easy as there is often a lack of information about the optimal seeding rate of individual species, which can vary depending on the location and the sowing time. In addition, plants of different species often react completely differently to each other than plants of the same species. This can manifest itself as competition but also as a synergy, for example if nutrients are taken from the soils in different amounts and in different ways, thus increasing the amount of nutrients available to plants, or if nutrients are exchanged directly between plants. The diagram below shows the how to put together cover crop mixture that are adapted to a specific farm or location, or how to evaluate commercially available mixtures.

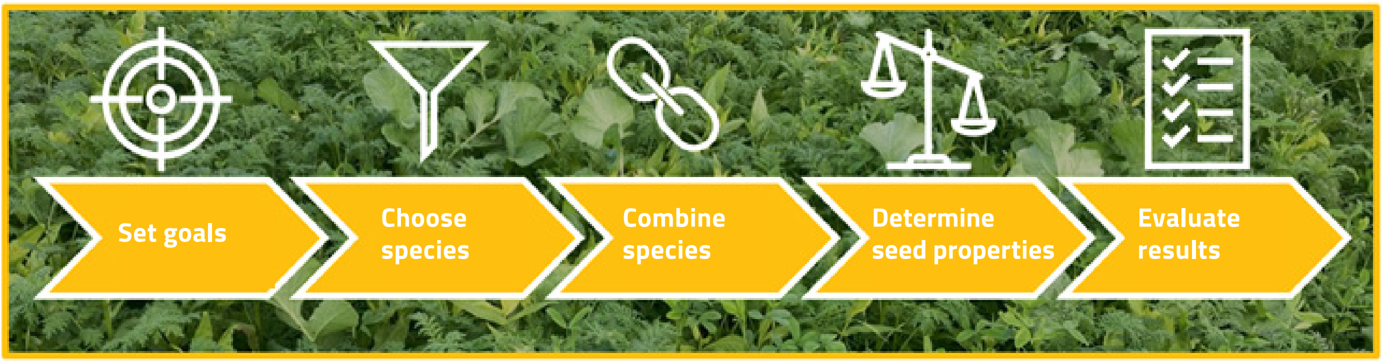


Fig. 3-2: Diagram for creating cover crop mixtures.

1. **Defining objectives**
   At the beginning, it is important to define the objectives that the cover crop cultivation should achieve. As a general rule, several objectives are set at a time which means that the tasks of a cover crop mixture should be prioritised. The objectives should be individually adapted to the conditions prevailing on the farm where the crops will be grown and oriented towards the type of farming, crop rotation, preceding and subsequent crops, or soil cultivation systems, for example.
2. **Choosing species**
   Next, the species suitable for the desired cover crop mixture must be selected out of the large pool of species available for cover crop cultivation. In addition to the choice of species, the selection of special varieties can also be considered. The choice of species is often very restricted by the main crops in the crop rotation. It is important to ensure that the reproduction cycles of pathogens, like those that cause clubroot in oilseed rape crop rotations, can be interrupted by the cover crop. The initial infestation and cultivation breaks of susceptible crops also play a role here. Of course, when choosing the species it must be ensured that they are capable of achieving the desired objectives under the prevailing conditions in the location where they will be planted. This means that the species selected must be able to fulfil the required tasks like nutrient conservation, nematode control, nitrogen fixing, feed suitability or soil structure stabilisation. Alongside these specific tasks, the species included in the desired mixture should also be capable of fulfilling the general agricultural requirements. In addition to providing a quick and sufficient soil cover to prevent erosion and encourage shade tilth, they should also ensure a safe and sufficient suppression of weeds and volunteer crops to avoid an unwanted proliferation of pathogens. Not all of the selected species must fulfil all objectives, but each task must be fulfilled by at least one of the species in the desired mixture. When choosing species, it is also important to take the requirements of the subsequent main crop into account. The ability to guarantee the dying off of the cover crop stand should be considered in order to prevent competition from "mature" cover crops. Likewise, it must be ensured that the cover crop does not prevent the creation of a suitable seedbed for the subsequent crop, which can happen if large amounts of cover crop residues are left behind. Shoot mass that has not frozen or a thick tangle of roots in combination with a small timeframe for the seedbed preparation can cause problems here. Finally, in drought areas it is important to carefully consider the selection of cover crop species to ensure that they do not compete with the main crop for water. All selected

species must be able to cope with the conditions of the location that they are planted in and the potential variability in the weather conditions that prevail at the planned sowing time. It is also important to remember that some species like white mustard are only suitable for late sowing, while others like some specific legumes are only suitable for early sowing. Finally, from an economic point of view the cost-benefit ratio of the seeds from the selected species must also be economically efficient.

3. **Combining species**
   This step is about combining the previously selected species into mixtures ensuring that the set objectives and their prioritisation can be adhered to as best as possible. There are some guidelines available to follow, but also some critical points that must be taken into account. A successfull combination of species in a mixture results when the interaction that leads to negative effects is avoided and interaction that leads to positive effects is enabled. This applies both to the above-ground growth and the root system of a cover crop. Negative interactions will become visible when, for example, the competitive behaviour within one or between different species leads to the generative development of the crops accelerating (Fig. 3-3). As a consequence little vegetative shoot matter is formed, and the shoot matter that does form lignifies quickly and stops root growth early. Positive interactions occur when species end up using different resource origins due to competition. In mixtures, a legume that competes with a non-legume for nitrogen may be forced to fix nitrogen from the air with help from rhizobia (Fig. 3-2). Certain plants like Tartary buckwheat mobilise the nutrient phosphorous when the dissolved form is used by other plants. To reduce the probability of negative interactions and increase the chance of positive interactions, as many different species should be combined in a mixture as possible. This can be achieved by using species from a range of different plant families (e.g. Brassicaceae, Poaceae, Asteraceae or Fabaceae). Combining species with different growth habits should also have a positive effect on the overall biomass of the mixture. In terms of the roots, these can be deep-, shallow-, fine- and coarse-rooted species that form a taproot or a tufted root system. With regard to the shoots, species that occupy different levels of a stand or that have supporting and climbing growth forms can be combined. Here it must be ensured that the distribution of space remains the same throughout all phases of growth in order to avoid late weed growth when empty spaces develop in the stand. All species that are combined in a mixture should have the same requirements in terms of sowing time but also have a certain degree of flexibility, as it is hard to predict exactly what the conditions will be like during the growth period. The sowing equipment available on a farm also has certain influence on which species can be combined. Separation of the seeds in the seed tank should be prevented and the different planting depth requirements of the various species must be observed.

4. **Determining the seed proportions**
   Once the species have been selected and combined, it is important to think about the optimal ratio of the different species within the mixture. To determine the composition of the seed mixture, people often divide the standard seeding rate for each species by the number of species included in the mix. However, it is rare that the optimal mix ratio is achieved with this method, and it is more often the case that the more competitive species dominate the mixture while the less competitive species do not come into their own. To prevent this from happening, the competitive abilities of the respective species must be taken into account. Crucifers, for example, are highly competitive while legumes are not. The competitive abilities of the crops also depend on the environmental conditions. For example, the competitive abilities of legumes increase significantly under conditions with limited nitrogen. The species-specific elasticity of the stand density-biomass-ratio must be taken into account: halving the seeding rate may not necessarily result in half the biomass. As a general rule, species that work well when grown on their own should be used as the main crop in the mixture. Species that are less successful when grown on their own, like certain species of clover for example, should not be underestimated as a support crop for the main cover crop. The prioritisation of the specific objectives that the cover crop mixture is designed to achieve also plays an important role when determiningthe seed ratios. For example, if nitrogen fixation has been given a higher priority than the uptake of nitrogen dissolved in the soil, the proportion of legumes in the mixture should be increased. This should only be done as

long as compliance with generally applicable agricultural requirements is not compromised. The overall seeding rate can more or less be based on the average of the usual seeding rate of the species in the mixture. However, due to the potential resource complementarity and niche differentiation, it can be assumed that the increase of the overall seeding rate has positive effects. Ultimately, when it comes to designing cover crop cultivation in the most cost-efficient way, the cost of the seeds plays an important role in the seed composition.

5. **Observing and evaluating cover crop mixtures in the field**
   Once the cover crop mixture has been created and sown, the growing stand in the field must be observed and evaluated to ensure that the objectives are achieved with the desired prioritisation. Likewise, if necessary changes need to be made to the mixtures to optimise the cover crop cultivation in the following year.

Fig. 3-3: Phacelia mixed with oil radish (left) shows signs of bleaching and reduced growth caused by a lack of nitrogen. Phacelia mixed with Egyptian clover (right) does not show any symptoms of deficiencies.

Fig. 3-4: Oil radish grown alone ceases vegetative growth and initiates flowering due to high intra-species competition (right), while the same variety sown at the same time in a mixture with phacelia, Egyptian clover and niger remains vegetative due to the lower competition.

INFOBOX

IN SHORT

- Cover crops can offer a range of agronomic, environmental and social benefits.
- Combining different species in mixture can expand the functions of cover crops further and increase their stability.
- Differences between arable farming systems and natural ecosystems can make it difficult to apply ecological theories to cover crop mixtures.
- Species-rich cover crop mixtures can improve nutrient uptake, stimulate soil biology, help to suppress weeds, and offer many other benefits.
- However, there is not necessarily a link between the variety of species in a cover crop mixture and the impacts they have on their ecosystem.
- This article has presented a procedure for selection and evaluation of cover crop mixtures.
- When choosing species for cover crop mixtures, it is important to consider the objectives and conditions of the farm and take into account the requirements of the subsequent main crop.

Infobox 3-1.

4. How cover crops influence soil structure and quality

Norman Gentsch, Georg Guggenberger

4.1 FORMATION OF SOIL ORGANIC MATTER AND CARBON

Soil organic matter, which is also widely known as humus, is an important indicator of the condition and quality of soils. All soil biological processes depend on the availability and quantity of organic matter in the soil. As soil organic matter consists of around 58 % organic carbon (C_{org}), this can be used as an indicator for measuring the humus content of soils.

The C_{org} contents are determined in a lab and converted into soil organic matter by multiplying by a factor of 1.72 (Infobox 4-1).

In the long term, cover crops help to increase the levels of soil organic matter in the soil. To get this result, a literature review of over 2000 data points from scientific works from around the world was conducted as part of this project. An annual global average C_{org} accumulation of 0.49 t per ha ($t\ ha^{-1}\ a^{-1}$) due to cover crop cultivation was calculated (96 % interval of confidence, 0.34 to 0.65 $t\ ha^{-1}\ a^{-1}$). This corresponds to an accumulation rate of soil organic matter of around 1 $t\ ha^{-1}\ a^{-1}$ and a CO_2 equivalent of 1.82 $t\ ha^{-1}\ a^{-1}$. The formation of soil organic matter is not an infinite process as at some point the soil reaches a condition that is typical for the location, where the gains and losses of C_{org} remain balanced.

The formation of soil organic matter is not linear, instead it slows down over time until a new balance is reached (Fig. 4-1). At the moment, we can only work out how much soil organic matter is ultimately formed by cover crop cultivation via statistical models. In an extensive literature review on various agroecosystems, the time required until the C_{org} content in the soil reaches a new equilibrium through intensive cover crop cultivation is estimated at 155 years[28]. Projections show that on average 16.7 t ha-1 C_{org} can be stored in the soil through long-term cover crop cultivation. For the Asendorf site, model calculations conducted as part of the CATCHY project show that a new equilibrium occurs after around 150 years (Fig. 4-1). In total, over this time the average C_{org} content in the topsoil (0-30 cm) could increase by 11.9 $t\ ha^{-1}$ (from 71.0 $t\ ha^{-1}$ to 82.9 $t\ ha^{-1}$). The data aligns well with the global values determined by Poeplau and Don[28] and illustrates the importance of cover crops for the humus content of soils.

The current data available about the formation of soil organic matter resulting from cover crop cultivation must be regarded critically. According to a recent study, there are too few studies that reliably describe the role of cover crops in humus formation and C_{org} sequestration[29]. None of the existing studies analysed samples from deeper soil horizons (>30 cm) or considered differences based on the equivalent soil mass. The concluding C_{org} inventory for areas examined during the CATCHY project at a soil depth of up to 90 cm is currently still in progress. The differences in soil density and changes to the equivalent soil mass through tilling will be taken into consideration here. The evaluation and provision of the data will be done at a later date.

Short-term changes in the soil organic matter content of soils are very hard to measure. Even the predicted formation rate of soil organic matter of 1 t ha^{-1} a^{-1} at the Asendorf site in the example calculation in Infobox 4-1 showed an increase in the C_{org} content in the topsoil of 1.40 % to 1.41 %. This very minimal difference of 0.01 % cannot be reliably measured. To make the annual influence of cover crops on the C_{org} content of the soil measurable, a stable carbon isotope was used to mark the cover crop biomass at the Asendorf site (the methodical principle is shown in Infobox 6-2 for nitrogen isotopes). Thanks to this technique, short-term changes in the soil carbon content, which usually take place while the cover crop is being broken down, can be measured.

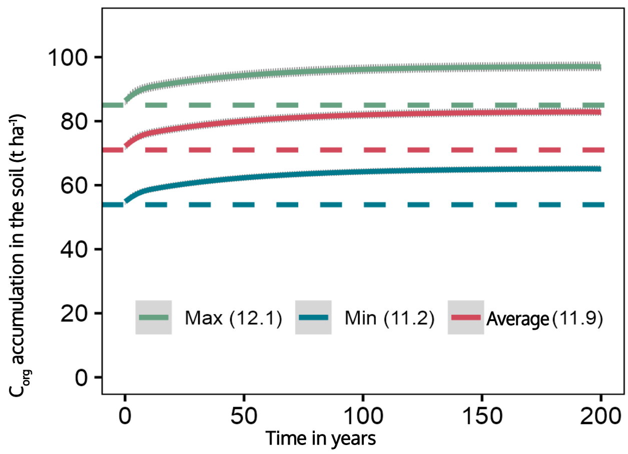


Fig. 4-1: Model of C_{org} accumulation in the topsoil (0-30 cm) through cover crop cultivation in a winter wheat - maize crop rotation at the Asendorf site. The dashed lines indicate the initial Corg content of the soil when in a state of equilibrium without cover crop cultivation. The linearity of the state of equilibrium is, however, a hypothesis. The state of equilibrium is actually more subject to cyclical variations. Colours indicate the three different models for the maximum, medium and minimum C_{org} contents of the trial areas. The curves show the progression of the C_{org} accumulation in the soil until the new equilibrium is reached (RothC model). The total growth after 200 years is given in brackets (in t ha^{-1}).

Fig. 4-2 shows that C_{org} inputs in the soil begin in December immediately after the cover crop has died off. Organisms in the soil break down the cover crop litter even with colder winter temperatures and form stable soil organic matter compounds. All investigated cover crops showed a significantly higher C_{org} input in the soil when compared to areas where the land had remained fallow. However, the variants also have different potentials. The 12-crop mixture proved to have the highest transfer rates in the soils (Figure 4-2), followed by phacelia and bristle oat. The lowest C_{org} inputs originated from mustard and the 4-crop mixture.

The carbon to nitrogen (C:N) ratio is an important factor in the efficient implementation of the cover crop litter. The 12-crop mixture has a low C:N ratio of around 15 in the shoot matter (Table 6-1). This is achieved through combining crops with high and low C:N ratios. This favours microbial processes and leads to an effective accumulation of soil organic matter in the soil (For more details, see chapter 5: Efficient nitrogen supply through microorganisms).

Cover crop cultivation is important for the formation of soil organic matter. In the long term, this not only soil fertility, but also store carbon in the soil in the form of stable soil organic matter compounds. As such, cover crop cultivation is a climate-relevant measure that can compensate some of the greenhouse gas emissions produced by agricultural activities.

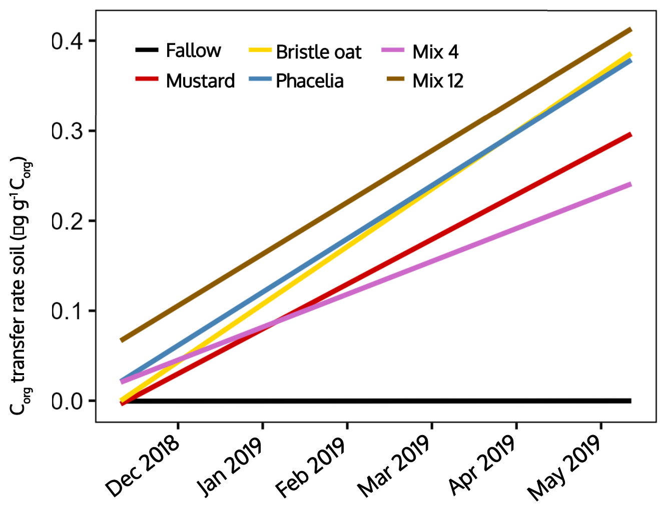


Fig. 4-2:Transfer rate of C_{org} from the cover crop litter to the soil. The data was determined using stable carbon isotopes and it represents the short-term changes in the soil C_{org} pool while the cover crop litter is being broken down.

INFOBOX

CONTENT OR RESERVES? IT'S IMPORTANT TO BE PRECISE.

When it comes to formation of soil organic matter, different terms such as "soil organic matter reserves", "soil organic matter concentration" or "soil organic matter content" are used, but they all have different meanings. As described at the beginning of this article, humus refers to all organic matter in the soil. However, the carbon, or more precisely the organic carbon (C_{org}), content of the soil is what is actually measured. In addition to C_{org} compounds, inorganic carbon (C_{inorg}) compounds can also be found in the soil. These mainly come from carbonate-rich stone, sediment or liming. To measure the carbon content, a soil sample is burned at high temperatures and the CO_2 that is released is measured. This is how the concentration of the total carbon (C_{tot}) is obtained. This includes the inorganic carbon. If the soils contain carbonates, they must be deducted from the total carbon.

$$C_{org}(\%) = C_{tot}(\%) - C_{inorg}(\%)$$

The term "content" refers to a concentration that is given either in mg g^{-1} soil or divided by 10
and given in %.
The term "reserves" includes the specific volume of the individual soil horizons and the total of the horizons until a specific depth. For a specific soil horizon, the C_{org} reserve is calculated as follows:

$$C_{org}\text{Reserve (t ha}_{-1}) = \text{SD (g cm}_{-3}) \times C_{org}(\%) \times \text{Depth (cm)}$$

Samples to determine soil density (SD) are taken from each horizon with a core sampler (most 100 cm^3) and dried in the laboratory at 105°C. The table below shows an example of the calculation of the C_{org} reserves in a soil profile from Asendorf site. The total of the three horizons at a depth of 90 cm produced a result of 71.3 t C_{org} ha^{-1}. Multiplied by a factor of 2, this produces a soil organic matter reserve of 142.6 t ha^{-1}. The so-called "Van Bemmelen Factor", valued at 1.724 is also commonly utilised in this context. The information about the depth is therefore very important when talking about reserves or when comparing locations.

HORIZON	DEPTH (CM)	SD (G CM^{-3})	C_{ORG} – CONTENT (%)	C_{ORG} – RESERVE (T HA^{-1})
Ap	30	1.3	1.4	55.6
Bv	30	1.5	0.8	12.7
Cv	30	1.6	0.2	2.9
Total up to	90			71.3

Infobox 4-1.

4.2 REDUCTION OF LEACHING LOSSES AND NUTRIENT BALANCE

One of the most important tasks of cover crop cultivation is to reduce nutrient losses from the agroecosystem. The aim is to keep any residual nutrients in the soil that could not be absorbed by the preceding crop or that are released when they decompose in the cover crop biomass and are rendered accessible for the subsequent crops. Even though nutrient losses cannot be completely prevented by cover crop cultivation, it can at least help to create very short nutrient cycles.

As mobile nutrients, nitrate (NO_3) and phosphate are particularly affected by leaching losses with seepage water. High nitrate or phosphate loads occur either in the form of excess nutrients leftover from the preceding crop, as a result of fertilising at the wrong time or due to a high mineralisation of crop residues. The latter can lead to excessively high nutrient loads in autumn in particular. At this time of the year, crop residues (straw, stubble, roots) are quickly mineralised due to the wet weather and increasingly high soil temperatures. This is particularly clear to see in the example of fallow land shown in Fig. 4-3. The autumn mineralisation between

September and November is shown as a green-yellow cloud here. After the harvest, a high nitrogen surplus of 50 kg ha^{-1} was measured. The autumn mineralisation increased the N_{min} values in the soil to 120 kg N ha^{-1}. The beginning of winter precipitation shifts the nitrogen into the subsoil. This is reflected in the increase in the N_{min} concentrations at a soil depth of 80 cm. In total, the N_{min} shift until the maize sowing below 80 cm was calculated at 102 kg ha^{-1}. At this depth, the nutrients are not available to the young crops and are therefore potentially at risk of leaching. Cover crops compensate for the high nitrogen loads in the soil and help to prevent nutrient losses. Fig. 4-3 shows the progression of the N_{min} contents of the soil over a period of ten months and after the vegetation of various cover crops. It is clearly visible that in autumn the cover crops absorb remaining nutrients and compensate the autumn mineralisation. As such when cover crops are grown, the N_{min} concentrations are not as high as when the land is left fallow (comp. Fig. 4-3 and Fig. 4-2). Clover sown in pure stand is not sufficient to buffer high nitrogen loads. In the trial, when Egyptian clover was used as a cover crop it only produced half the biomass of other crops, and it also made use of atmospheric nitrogen with help from rhizobia. In the trial shown in Fig. 4-3, the cover crop termination was done mechanically when the first frost happened at the beginning of November. Thus, the soil analyses could all be conducted at the same point in time. If cover crops that die off later or winter hardy crops are used, the initiation time of mineralisation is delayed accordingly. The mineralisation of the cover crop litter begins immediately once the cover crop undergoes senescence (dashed line in Fig. 4-3). Particularly with mustard and clover, but also with mixtures, the mineralisation of nitrogen-rich leaf matter results in increased N_{min} concentrations in topsoils. Similar to the case of fallow land, the freshly mineralised nitrogen from the cover crop biomass left in the soil is exposed to displacement processes over winter. The N_{min} quantities that were washed out of the rhizosphere before the maize was sown are marked in red in Fig. 4-3. Bristle oat, phacelia and the 12-crop mixture showed the lowest losses, whereas mustard, the 4-crop mixture and particularly clover showed significantly higher amounts of N_{min} in the subsoil.

Three factors influence the N_{min} pools in soil during cover crop cultivation:

1. The cover crop species: e.g. legumes or non-legumes, winter-hardy or frost-sensitive.
2. C:N ratio of the cover crop biomass: The lower this ratio is, the quicker the mineralisation.
3. Time of the dying off/killing off: The earlier this occurs, the greater the extent of mineralisation over winter.

The smaller the C:N ratio of the cover crop is, the narrower the time gap between the plant litter incorporation and the sowing of the subsequent crop should be. Cover crop litter is rich in structural materials (such as the stems of white mustard or sunflowers) with a high C:N ratio. However, this can cause a temporary nitrogen block in the soil if the plants' incorporation into the soil is delayed. Subsequently, mixtures can compensate for the weaknesses of individual species. Therefore, they do not supply a wide range of nutrients (see Chapter 6), but also a rapid nutrient release for the subsequent crop without high losses.

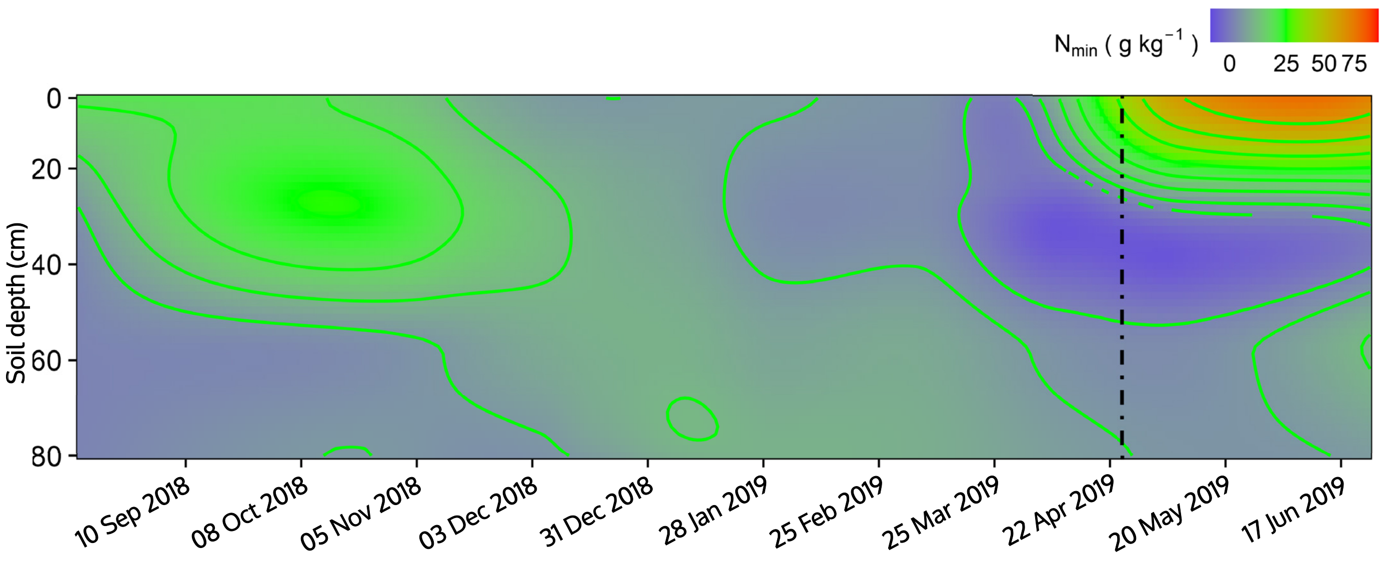


Fig. 4-3: Continuous measurements of N_{min} in the soils left fallow from autumn 2018 to summer 2019 at the Asendorf site. The dashed line marks the maize sowing and the nitrogen fertilisation. The colours describe the changes to the N_{min} concentration over time (x axis). The N_{min} losses from the soil profile totalled 102 kg ha^{-1} until the maize sowing.

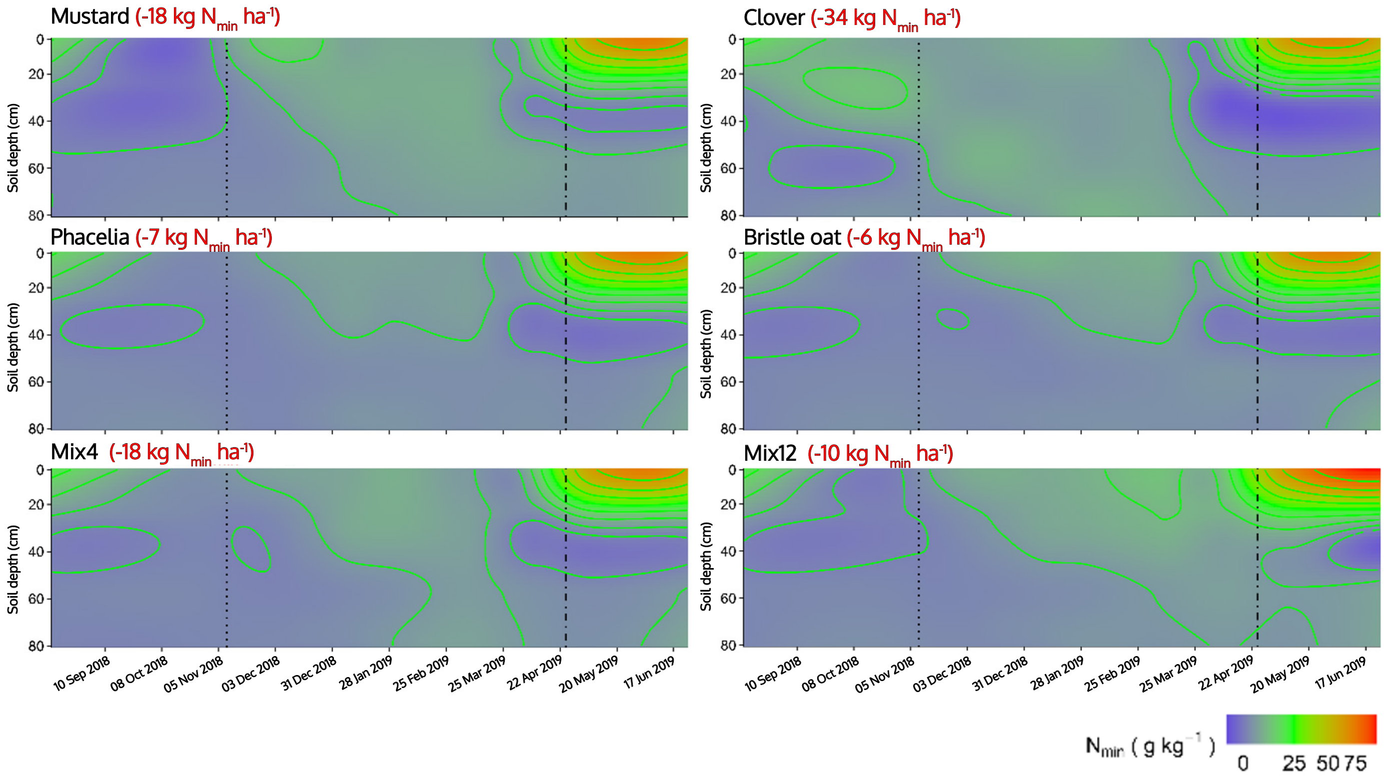


Fig. 4-4: Continuous measurements of N_{min} in the soils sown with different cover crops from autumn 2018 to summer 2019 at the Asendorf site. The dashed line marks the dying off of the cover crop in 2018 and the maize sowing with nitrogen fertilisation in 2019. The colours describe the changes to the nitrogen concentration over time (x axis).

4.3 SOIL STRUCTURE AND WATER BALANCE

The soil structure is an important indicator of the soil condition and its fertility. Soil structure refers to the structure of solid soil particles and the pore space between them. It is an important control parameter for water and nutrient flows, gas exchanges with the atmosphere and biological activity. A good soil structure reduces waterlogging and makes the soil easier for roots to penetrate, meaning that more water and nutrients are made available for plant growth. The cultivation of cover crops can improve the soil structure within the limits of the soil type (texture) and soil chemical parameters. Crops can influence the soil structure in a range of direct and indirect ways:

1. **Root morphology** - differences in the crops in terms of rooting depth, root density and root diameter have an impact on the biopores in the soil;
2. **Root exudates** - root exudates act as a binding agent for particles;
3. **Litter**- the decomposition of energy-rich litter mobilises polysaccharides as a binding agent for soil particles;
4. **Soil organisms** - crops influence the microbiome in the rhizosphere (see Chapter 3), soil fungi in particular are a key factor in aggregate formation.

A range of different effects on the soil structure can be achieved depending on which crops are chosen as cover crops or main crops. For example, studies have shown that the macroporosity and aggregate stability of soil while different cover crops are growing depends on the root morphology of the crops[30]. The aggregate stability is an important indicator of the condition of the soil structure. There is usually a mix of different sized aggregates in soil. Macroaggregates consist of smaller aggregate classes that are kept together by organic binding agents. Larger aggregates in the soil favour larger pore diameters and thus improve the water, air, and nutrient flows in the soil. In a laboratory, the stability of the soil aggregatesis measured based on an application of a defined force (e.g. with water). The greater the amount of aggregates that withstand this force, the more stable the soil structure in the field is against the effects of stress.(e.g. harmful compaction, risk of erosion).

The aggregate stability of the different cover crop treatments was measured in the CATCHY long-term trial after the second cover crop. To exclude the direct influences of the various crop species, the measurements were not conducted during the cultivation of the cover crop but with the winter wheat. Fig. 4-5 shows the mean weight diameter (MWD) of water-stable aggregates. The higher the MWD, the larger the mean weight diameter of the soil aggregate after force has been applied with water. All crop rotations with cover crops show a 10 % to 19 % higher MWD compared to areas that are left fallow. Except from bristle oat, the differences to fallow areas were statistically significant (Fig. 4-5). The highest MWD was measured with the 12-crop mixture, followed by the 4-crop mixture and Egyptian clover sown on its own. The statistical model calculations showed that cover crop mixtures had a higher MWD improvement potential (16 %) than single crops (12 %). In addition, regression analyses showed that more C_{org} is accumulated in larger aggregates. This indicates that cover crops release organic binding agents into the soil which contribute to the formation of larger and more stable aggregates[31].

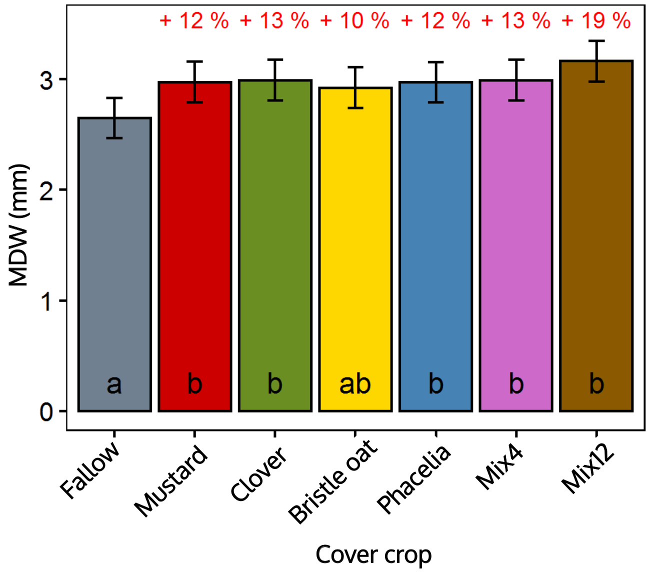


Fig. 4-5: Influence of cover crops on the mean weight diameter (MWD) of water-stable aggregates. Small letters show the affinity of statistically different treatments. The red values indicate the increase in the MWD in per cent in comparison to the fallow areas.

Each tillage (e.g. seedbed preparation) leads to changes in the aggregate structures and thus changes to the pore volumes in the soil. Loosening the soil increases the volume of large pores which is profitable for germination and aeration.Conversely, on the other hand, tilling can also reduce the water-storing capabilities of the important medium-sized pores which disrupts macroaggregates and pore systems. This can have a negative impact on the soil's susceptibility to erosion and the soil water reserves available to the crops. Cover crops can at least partially compensate the negative effects of the tilling. All investigated cover crops proved to be helpful in improving the aggregate stability, with biodiverse cover crop mixtures showing the highest potential. In the trials, the improvements could be seen after the third complete crop rotation (i.e. after six years and two cover crop cultivations). As such, it can be concluded that the long-term establishment of cover crops as a fixed part of the crop rotation helps to improve the formation of larger and more stable soil aggregates.

SUMMARY

The lasting integration of cover crops in a crop rotation leads to an increase in the soil's content of soil organic matter in the long term. As long as cover crops remain an integral part of the crop rotation, they can also store carbon in the soil. The amount of fixed carbon is heavily dependent on the characteristics of the location, such as the climate, soil type and hydrology. The management and starting level of the humus content at the beginning of the cover crop cultivation also plays a decisive role. In well-supplied, humus-rich soils, soil organic matter formation due to cover crops is lower than in soils with low humus contents to begin with.

Furthermore, cover crops are also an essential tool for efficiently managing nitrogen and other plant nutrients as nitrogen losses are reduced to a minimum when the right cover crop species or mixture is used. The exploitation of nutrients from the soil reserves can be supported through the selection of the right cover crop. The release of nutrients from the cover crop biomass must be considered in the long term over several subsequent crops. The C:N ratio of the cover crop biomass plays a crucial role for the immediately subsequent crop, but it becomes less important the more it decomposes.

Cover crops improve soil structure and water balance. They result in the formation of more stable and large soil aggregates and can, to a certain degree, offset negative impacts of tilling. In particular, cover crop mixtures have been proven to have a very positive impact on aggregate formation and water availability.

INFOBOX

IN SHORT

- In the long term, cover crops help to increase the level of soil organic matter in the soil. It requires a permanent establishment of cover crops in the crop rotation and an equilibrium in the soil organic matter content at the beginning of the measure.
- Cover crops minimise nutrient losses in arable soils.
- In the first subsequent crop, the release of nutrients from the cover crop biomass largely depends on their C:N ratio.
- Cover crops encourage the formation of soil aggregates and their stability.
- Cover crops can partially compensate for the negative influences that tilling has on soil structure.

Infobox 4-2.

5. A look under the surface: how cover crops shape the rhizosphere

Barbara Reinhold-Hurek, Thomas Hurek, Michał Oskiera, Norman Gentsch

Regardless of whether it is a cover crop or a main crop, all crops live together in a community with countless microorganisms. This community is known as a microbiome. Crops have developed together with their microbiomes and have built up many relationships with them over the course of millions of years. This very complex ecosystem works like a massive organism and in science it is called a holobiont. Each member of the community fulfils specific functions in the system and the interactions between all the different components produce a functioning equilibrium.

Crop species have different requirements when it comes to nutrient supplies, or they can be affected by specific pathogens. As non-mobile organisms, they are even more reliant on coming into contact with their environment as animals. This means that crops actively excrete signalling substances through their roots in order to encourage the growth of some of the many microorganisms present in the soil that can be of use to them. The crops also excrete antimicrobial substances (like glucosinolates) to suppress the growth of pathogenic groups of organisms, for example. As a result, each species of crop establishes a very specific microbiome in their immediate root environment and so creates a unique rhizosphere (see Infobox 5-1). This rhizosphere microbiome is a type of microbial fingerprint that the crop species - and even varieties - leave behind in the soil. In holobiont ecosystems, crops supply microorganisms like bacteria and fungi that live on, in and around them with sources of energy such as sugars that they have produced through photosynthesis. In turn, the microorganisms help the crops with their nutrient supply, but also with their immune defences or stress management. By combining different species of crops, e.g. in cover crop mixtures, we end up with a wide range of chemical compounds in the rhizosphere. The same applies for the composition of the shoot and root litter (see Chapter 6, Element composition). Crop exudates, litter and soil organic matter are the main sources of nutrients for microorganisms in the soil and - depending on the chemical properties - have different effects on the growth of microorganism groups.

In the CATCHY project, the microbial fingerprint in root-free soils, in rhizosphere soils and in the roots of different cover crops sown individually and in mixtures was investigated. Microbial fingerprints can be obtained from gene sequences that can be sequenced in their thousands with modern technology (see Infobox 5-2). The results clearly showed that different crop species host different bacteria on their roots. Individual cover crop species like mustard, bristle oat and Egyptian clover were largely colonised by the same bacteria, but there were certain bacteria that were only found to be present on one species of crop (Fig. 5-1).

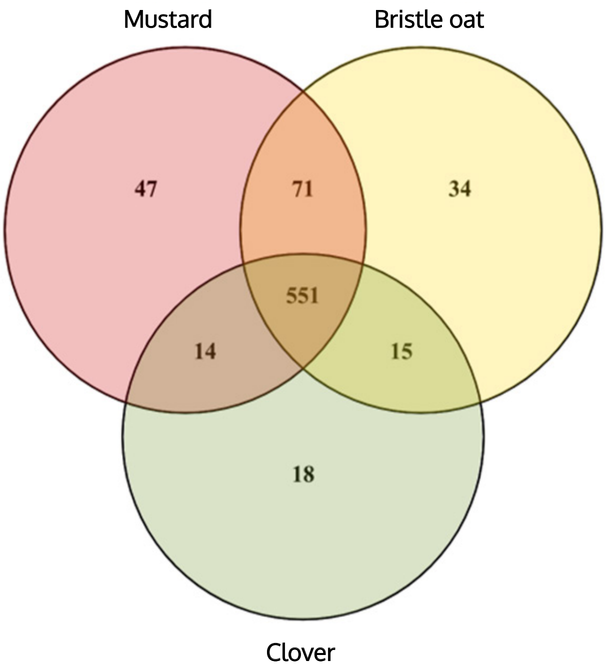


Fig. 5-1: Bacterial DNA in the roots of various cover crops (mustard, bristle oat, clover) grown at the Asendorf site was analysed. The diagram shows the overlaps and differences of the different genera of bacteria found in the roots; the numbers indicate the number of genera. E.g. 551 genera were found in all three species of crops.

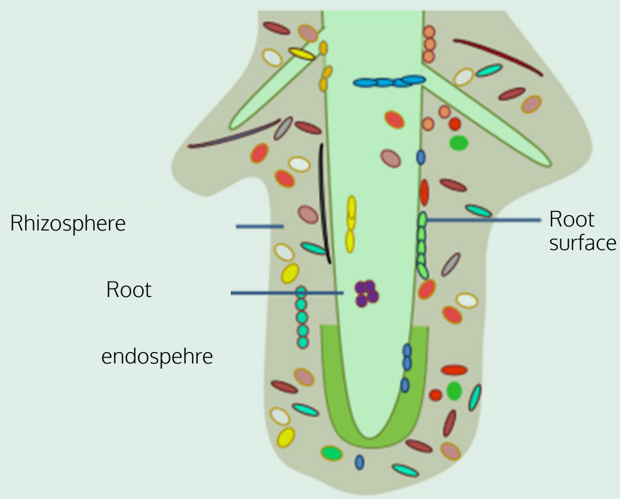
The large number of bacteria that colonise all crop species can be explained by the fact that all the crops are grown in the same arable soils. One of the bacteria found was Pseudomonas, a genus of bacteria that includes many species of bacteria usually associated with crops. Many of these bacteria help to suppress crop diseases or encourage crop growth. The microorganisms that appear with just one species of crop play an interesting role when it comes to analysing the influence of the cover crop species on the microbiome. For example, Nitrobacter was only found with clover and is a bacteria involved in the conversion of nitrogen in the soil. Through the difference substances excreted by the roots and the decomposition of the different litter, cover crops can change the community of microorganisms in the soil (Fig. 5-2) and in the subsequent maize crop too.

In some cases, cover crops were observed to have an influence on the microbial diversity in the soil. In simple terms, microbial diversity refers to the number of species or groups of microorganisms present. In some years, after both evaluated cover crop mixtures (4-crop and 12-crop mixtures) were examined during the vegetation period of the main maize crop, a trend towards a higher bacterial diversity was observed in comparison to land left fallow or planted with a single crop (Abb. 5-2). Alongside bacteria, fungi are also part of the microbiome. Next to the well-known mycorrhizal fungi, many other fungi colonise the roots. The diversity of the root fungi is likewise influenced by cover crops.

INFOBOX

THE RHIZOSPHERE

"Rhiza" is the Greek word for root. The rhizosphere is the thin layer of soil that the crop roots adhere to. It is a hotspot for microorganisms that are under the direct influence of the crops. Bacteria also colonise the surface and even the inner areas of the roots (the root endosphere). The crop rhizosphere is the most species-rich niche for bacteria. Analyses have shown that the rhizosphere has a greater microbial diversity than the surrounding soil itself and the roots. The rhizosphere is also the place where the crops receive their water and nutrients. The crops secrete special chemical compounds from their roots that encourage the growth of certain groups of soil microorganisms.



Infobox 5-1.

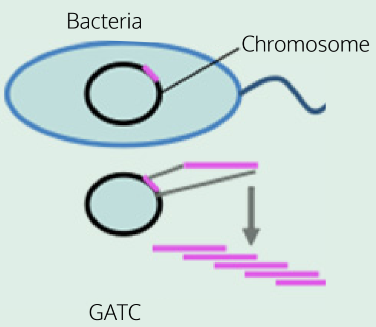
It was observed to be particularly high in maize roots after the cultivation of the 12-crop mixture (Fig. 5-3). Whether the soil remains fallow and free of vegetation or whether it is planted with cover crops, either planted alone or in a mixture, plays a role for the microbial community.

INFOBOX

SEQUENCING FOR CHARACTERISING THE MICROBIOME

Analysis of microorganism marker genes from environmental samples:

- Extraction of the genetic material (DNA)
- Reproduction of the marker genes (for ribosomal RNA: 16S rRNA)
- Sequencing of the base sequence and bioinformatic sequence comparison of up to several million sequences at the same time



Infobox 5-2.

5.1 WHY IS THE DIVERSITY OF THE MICROBIAL COMMUNITIES IN SOIL SO IMPORTANT?

A higher microbial diversity in the soil improves the function of the ecosystem, making it more resistant to disturbances[32,33]. A high microbial diversity means that important ecosystem functions, like the production of enzymes or other compounds, compensate for different members of the community. If vital groups of microorganisms disappear due to environmental disturbances, e.g. due to a change in the pH level of the soil, the growth and activity of other members of the community that fulfil similar functions can balance this out. As such, the diversity is almost like a type of insurance that ensures that all soil functions can be maintained despite species losses due to environmental changes in soil biology. The cultivation of cover crop mixtures in particular can encourage the development of more diverse microbiomes in the soil. After a main crop has been sown, the young seedlings may find a different microorganism community in the soil if planted after a fallow period instead of after cover crops (Fig. 5-2, 5-3). Crops usually recruit their microbiome from the soil. This means that the vegetation history of the soil is important for the microbiome in and on the crops. The higher the microbial diversity in the soil, the more diverse the groups of microorganisms available for the crops to choose from. This also expands the spectrum of relationships that can be established between crops and microbes.

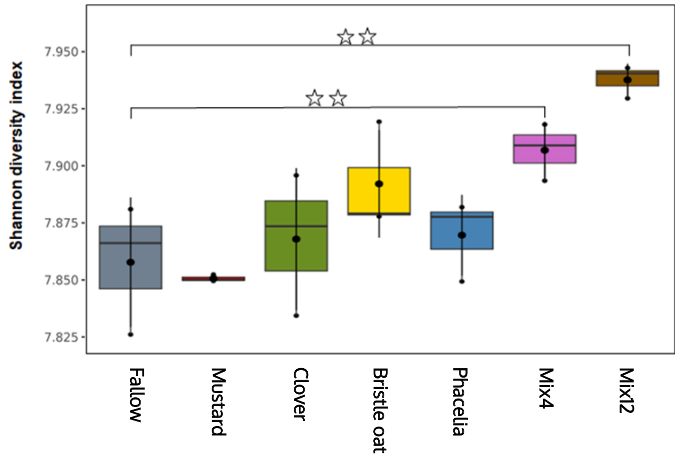


Fig. 5-2: Variety of bacteria in the soil following cover crop cultivation at the Triesdorf site. This shows the diversity of the bacteria in the soil during the growing period of the subsequent maize crop following the cultivation of a range of individually planted cover crops, mixtures, or a fallow period. Diversity index: Shannon. Asterisks indicate significant differences.

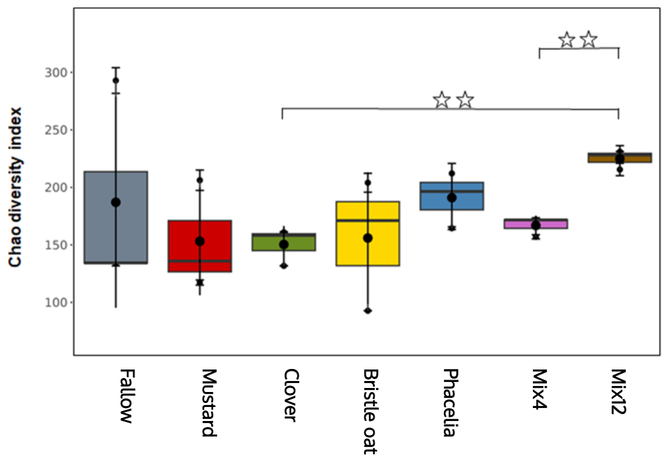


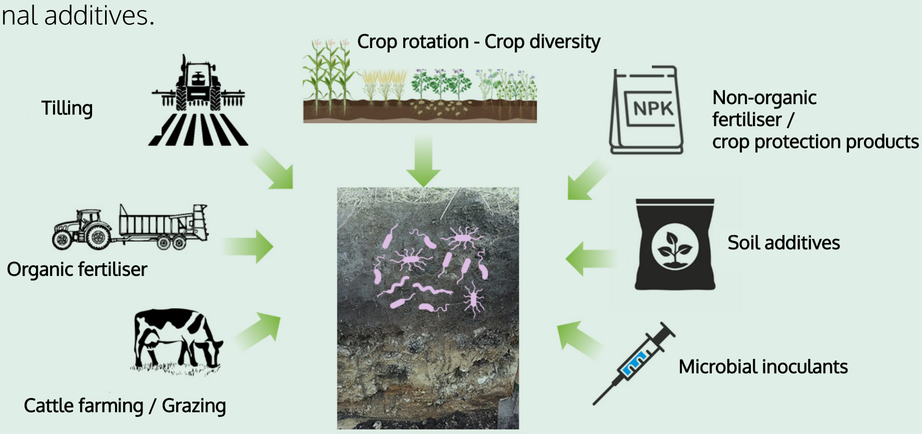
Fig. 5-3: Diversity of fungi in and on maize roots following cover crop cultivation at the Asendorf site. This shows the diversity of the root-related fungi during the growing period of the subsequent maize crop following the cultivation of a range of individually planted cover crops, mixtures, or a fallow period. Diversity index: Chao. Asterisks indicate significant differences.

The higher the diversity of microorganisms that a crop can get from the soil, the more advantageous this is for the nutrient uptake and health of the crops. Lower microbial and fungal diversity was observed in crops containing diseases or pathogens[34,35]. All soils microorganisms that support crop growth but also pathogens that can have a negative influence on plant growth. The aim of cover crop cultivation here is to stimulate enough microorganisms in the soil to encourage crop growth and enough opponents, so-called antagonists, to stop the spread of pathogens (Infobox 5-3).

INFOBOX

BIOENGINEERING VON MIKROORGANISMENGEMEINSCHAFTEN

This refers to measures that increase the number of certain groups of microorganisms in the soil that are expected to have positive effects on crop growth and soil health. The diagram gives an overview of measures that influence the composition of microbial communities in the soils. Important microbial groups that have been proven to have a positive influence on crop growth include rhizobia (nodule bacteria on legumes), mycorrhiza, plant growth-promoting rhizobacteria (e.g. Pseudomonas, which increases the solubility and availability of iron for crops), microorganisms that dissolve phosphate (e.g. bacteria from the genera Pseudomonas, Bacillus, Enterobacter, Burkholderia, and Pantoea, as well as fungi from the genera Penicillium and Aspergillus), or organisms for biocontrol that tackle crop pathogens (e.g. Bacillus bacteria, or fungi from the genera Trichoderma and Gibellulopsis). The crop rotation and crop diversity on the field are important tools when it comes to influencing microbial communities and functions. Cover crops can be a tool to stimulate positive microbial functions in the soil without the need for additional additives.



Infobox 5-3.

To find out whether cover crops could also have a decisive influence on the microbiome in the subsequent maize crop, samples of living maize roots were taken. The subsequent studies of the microbiome produced surprising results. Certain microorganisms were only detected or appeared more frequently in maize roots after very specific cover crops had been cultivated. For this purpose, taxonomic investigations to determine the composition of fungal genera in maize roots were conducted. Interestingly, these analyses showed that the most frequently found species of fungi (Fig. 5-4) in the fungal microbiome was not mycorrhiza. Mycorrhiza from the Glomeromycota division were only found in small numbers in the maize roots. However, a whole host of useful fungi that live in and on the maize roots were found. These were mainly enriched by the cultivation of Phacelia and the 12-crop mixture. Both cover crop variants led to a significant increase in certain genera of Sordariomycetes and Mortierella, but suppressed species of Gremmenia, which often contain pathogens.

The class of Sordariomycetes includes several fungal genera that contain plant growth-promoting and pathogen-suppressing species (e.g. Acremonium, Cladorrhinum, Exophiala). The genus Mortierella has biocontrol strains that fight against nematodes or phosphate-mobilising strains. Another important discovery was that the Gibellulopsis genus was the most frequently seen fungi in maize crops following the cultivation of the 12-crop cover crop mixture and phacelia. These fungi are effective as a method of biocontrol against the pathogens that cause Rhizoctonia solani root rot and Verticillium wilt. Furthermore, after all cover crop treatments a new fungal genus, Metacordyceps, appeared that had not been observed in land that had been left fallow. Metacordyceps is a very special entomopathogenic fungi which affects the larvae of harmful insects and nematodes. Fungi of the genus Fusarium were most frequently found after mustard was cultivated or after land was left fallow, and least frequently found after phacelia was cultivated. This indicates that phacelia is the most effective crop to counter the spread of these pathogens. Fungi of the genus Endogone were only found in bristle oat and Mix4, which contains bristle oat, and the subsequent maize crop. The genus recycles dead crop tissues and is therefore important for nutrient cycles.

Bacterial communities also showed some interesting changes. In particular, after the cultivation of the 12-crop mixture the nitrogen-fixing Nitrospirillum, Derxia and Leptothrix were detected in higher quantities in maize roots, while the typical soil bacteria Geobacter decreased compared to all other cover crop treatments. These results indicate that microorganisms with a positive influence on the nitrogen cycle in crops are promoted by the one-time cultivation of species-rich cover crop mixtures.

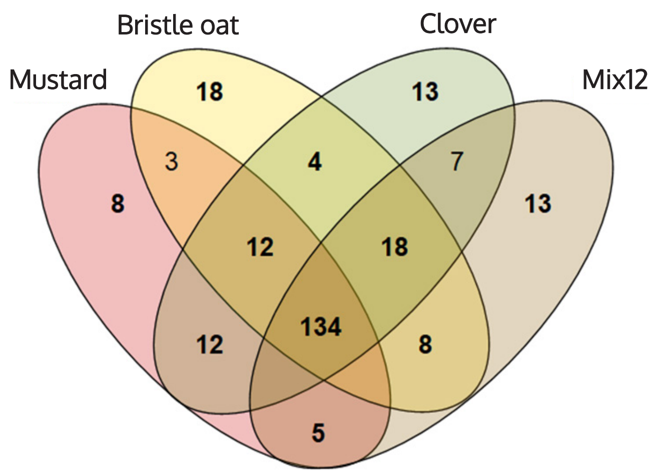


Fig. 5-4: Fungal DNA in maize roots after the cultivation of various cover crops at the Asendorf site. The diagram shows the overlaps and differences of the different genera of fungi found in the roots; the numbers indicate the number of genera. For example, 134 of the same genera were found in maize roots after all 4 cover crop types.

Cover crops can be an effective and environmentally friendly option for influencing the composition of the microbiome in agricultural soils (see Infobox 5-3). The increase in crop diversity in cover crop cultivation can result in a greater diversity in the microorganisms in the soil. The crop rotation should remain a key consideration here as well. If certain crop species are cultivated too closely together, this can lead to an accumulation in pathogens in the soil. However, further research is needed to make more concrete statements about which crops influence which microbial groups in the soils.

5.2 EFFICIENT NITROGEN SUPPLY THROUGH MICROORGANISMS

The soil microbiome of land used for agricultural purposes is not only important for plant symbioses and defence against pathogens. Almost all soil functions are linked to microbial processes. The decomposition of organic matter and crop residues is one of the most important ecosystem functions of microorganisms. During the decomposition process, nutrients are released in plant-available form and a large part of the carbon from the biomass is respired as CO_2. Part of the non-respired carbon is required to build up the biomass of microorganisms. Microbial biomass is therefore an important store and source of carbon and crop nutrients.

A medium-quality arable field usually has 500 to 600 kg ha^{-1} of carbon in the topsoil in the form of microbial biomass[36]. Another 100 to 160 kg ha^{-1} in the form of nitrogen (Nmic) and around 40 kg ha^{-1} in the form of phosphorous (Pmic) is stored in the microbial biomass. The conversion times for nitrogen and particularly phosphorous in the microbial biomass are comparably short. The annual nitrogen flow through the microbial biomass is around 80 to 100 kg ha^{-1}, and the phosphorous flow around 10 to 40 kg ha^{-1}. This means that a large part of the crop nutrition on the field happens through cells of microorganisms. In view of this, the aim should be to have agricultural soils with the highest possible level of microbial biomass with high conversion rates[36].

Cover crops fulfil exactly this function. They increase the microbial biomass in soils and so ensure faster and more effective nutrient cycles. The measurements taken at the Asendorf site show that the annual variations of the Nmic in topsoils on land without cover crops (fallow) can range from 25 and 230 kg ha^{-1} (Fig. 5-5). With cover crops, the annual Nmic variations were less extreme, ranging from 50 to 200 kg ha^{-1}. A significant drop in the N_{mic} level is seen in winter in particular, when there are no living crops covering the soil. Even in summer, competition between crops for water and nutrients results in a significant reduction in N_{mic}. The highest microbial biomass and thus the highest Nmic reserves can usually be found in early spring/early summer and autumn. At this time, the soil temperature and water contents are at optimal levels and competition between living crops is low. Like cover crop biomass, the microorganism biomass acts as a sink and source for nitrogen in the soil. Over winter, there is constantly between 15-50 kg ha^{-1} more nitrogen in the microbial biomass under cover crops (Fig. 5-5).

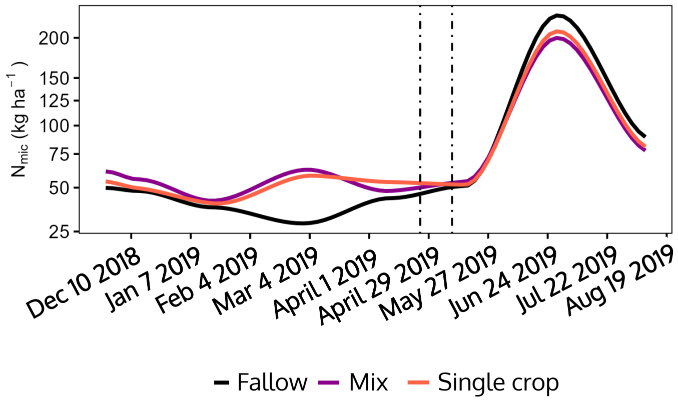


Fig. 5-5: Progression of nitrogen in the microbial biomass in the topsoil on the Asendorf site. The lines show the mean of different sample data. The dashed lines show the sowing and fertilising of the main maize crop.

Similar to crop biomass, this nitrogen is temporarily protected from leaching. At the same time, the microbial biomass has a better supply of nitrogen than fallow land which means that microorganisms are less nitrogen limited. Microorganisms that are less nitrogen limited contribute to a more efficient formation of soil organic matter and reduce carbon losses into the atmosphere. After a mineral fertilisation of the main crop, a good nitrogen supply to the microbial biomass is also beneficial. As better-supplied microorganisms do not suffer from a lack of nitrogen, there is also a lower nitrogen immobilisation from the applied mineral fertilisers in the microbial biomass compared to the fallow land (Fig. 5-5 lower maximum amplitude). After a cover crop cultivation, the microbial biomass does not compete with the main crop as much for the plant nutrients in the soil compared to when there has been no cover crop planted. The evaluated cover crop mixtures consistently showed a slight improvement in the above-mentioned cycle when compared to a single species of cover crop sown on its own. Both, the microbial biomass and the microbial nitrogen supply are optimised by cover crop mixtures. One of the main reasons for this is the improvement of inputs into the rhizosphere and the quality of the cover crop litter. The carbon to nitrogen ratio (C:N) in the cover crop biomass is a good indicator of how efficiently microorganisms can convert litter and mobilise nutrients (see Chapter 6, Nutrient uptake). By managing the C:N ratio in the cover crop biomass, microbial conversion processes and even the composition of the microbial species spectrum can be influenced.

A balanced and stable milieu for microorganisms in the soils means better support for the crops with the uptake of nutrients and water. Through their root activity and biomass production, the cover crops create a basis for stable, microbial populations in the soil. The increased, microbial activity results in more efficient microbial nutrient cycles in the soil and in a better supply of nutrients for the plants. On average, around 1.8 % of the total organic carbon on the fallow land at the trial site in Asendorf is stored in the microbial biomass each year. When cover crops are used, this figure rises to 2.1 %. This increases the annual conversion rates of carbon by the microbial biomass by 15 %. As such, cover crops offer greater potential for the formation of more stable soil organic matter compounds from microbial remains. Cover crop cultivation contributes to the increase in the storage of CO_2 from the atmosphere in the form of microbial biomass and formation of soil organic matter in the soil.

INFOBOX

IN SHORT

- Crops have a complex microbiome consisting of microorganisms that live in their tissues and in their rhizosphere.
- Different species of crops have a different microbiome in their roots and rhizosphere.
- The cultivation of cover crop mixtures can increase bacterial and fungal diversity in soils and thus boost the resistance of the ecosystem.
- Cover crop mixtures can also influence the microbiome of the subsequent main crop. For example, useful fungi accumulated in maize roots after the cultivation of highly diverse cover crop mixtures.
- Cover crops improve microbial biomass and the nutrient cycle, resulting in a more efficient nitrogen supply and fewer carbon losses.

Infobox 5-4.

6. How cover crops influence nutrient balances

Diana Heuermann, Nicolaus von Wirén

Nutrient losses are a major problem in modern agriculture. To achieve optimal yields, the nutrient requirements of the main crops must be covered. However, for various reasons fertilised nutrients are often not used effectively to produce yields. For example, maize needs the most nutrients while it is growing, when a fertiliser application with standard equipment is no longer possible. As such, fertiliser must be applied early and, followed by a one- to two-months period during which nutrients may be leached out or is gaseos emmission. While other crops like oilseed rape have a more efficient nutrient uptake, they do show major deficits when it comes to recycling nutrients from the vegetative organs (leaves, stem, roots) in the seeds. As such, after the harvest many nutrients remain in the straw and on the field[37]. With sufficient soil moisture levels and temperatures, the crop residues in the soil are decomposed by means of microbial degradation, resulting in high nutrient excesses or losses before the subsequent crop is established. These can range from 25 to > 200 kg of nitrogen per hectare depending on the main crop, management, location, and weather conditions[38-41]. A critical phase of nutrient loss comes after the harvest of the main crop and during the increasingly wet autumn and winter months. Such nutrient losses can be reduced by cover crop cultivation. Cover crops can absorb the nutrients and thus protect them from leaching, conserve them in their biomass over winter and then release them while the following main crops are growing. As such, cover crops can help to close nutrient cycles and keep nutrients dynamic in the system.

6.1 NUTRIENT UPTAKE

In order to achieve optimal nutrient management with cover crops, first of all it is important to evaluate the nutrient balance and release after the preceding main crop at the location (e.g. weather, soil conditions) and adapt the choice of cover crop in view of the possible nutrient surplus and losses. The effectiveness of the nutrient uptake is significantly affected by the selected cover crop species. Rapidly growing species like white mustard or oil radish planted alone offer an advantage over slow-growing species when it comes to nutrient accumulation due to their high biomass growth, which is particularly important with late sowing in autumn. In addition, the size and shape of the root system and the specific nutrient acquisition mechanisms determine the nutrient uptake of individual plant species. A deep rooting system, like that of white mustard or oil radish (Fig. 6-1), offers the advantage of ensuring that easily leachable nutrients like nitrogen in the form of nitrate or sulphur in the form of sulphate are absorbed from the lower layers of soil and so saved from being washed out into the groundwater. In topsoils, the branched root systems of plants like phacelia, bristle oat or field pea (Fig. 6-1) can effectively exploit nutrients that are less mobile in soils. This includes nutrients like phosphorous and potassium, which are often present in poorly soluble compounds[43].

In addition to the larger uptake surface in the topsoil, special mechanisms to exploit these nutrients also play an important role. Crops actively release root exudates into the soil to increase the concentration of nutrients available to them. Organic acids and phenolic compounds can, for example, dissolve phosphate from compounds with iron, calcium or aluminium, while certain enzymes, known as phosphatase, make phosphate from organic metals available in the soil[44,45]. Plants also release chelators to mobilise iron. These bind with the Fe^{3+} present in the soil and transport it to the roots[46,47]. Alongside these direct effects of root exudates on nutrient exploitation in the soil, crops also influence the soil microbiome in favour of their nutrient uptake. For example, some grasses release inhibitors that stop ammonium from transforming into nitrate in the soil. These are known as biological nitrification inhibitors (see Infobox 6-1). As a result more nitrogen in the form of ammonium, which is less as risk of leaching, stays in the soil[48,49]. Through a symbiosis with rhizobia, legumes are able to improve their nitrogen content[50], and many species of crops actively promote symbioses with mycorrhiza in order to expand their root surface for their nutrient uptake. In a crop mixture, the nutrient extraction strategies of different species of cover crops are optimally combined. However, when creating a crop mixture, care must be taken to ensure a competitive strength of the different species, otherwise slow-growing crops can be suppressed by other fast establishing crops. For example, Fig. 6-1 clearly shows how white mustard and Phacelia dominate the mixture and bristle oat and Egyptian clover are almost completely prevented from growing. While the nutrient exploitation potential of bristle oat and Egyptian clover are indeed less important in this example mixture, overall the mixture can form biomass and acquire various nutrients (Fig. 6-2) just as well as the best species sown on their own[51]. This phenomenon was observed in a total of eight different trials. Thus, a mixture is a better option for a stable, best-possible nutrient acquisition over single crops sown on their own. Until the end of the vegetation period, cover crops can bind very different quantities of nutrients depending on the selected species or mixture, the location and weather conditions, the sowing time and the crop management. This can range from 40 to 200 kg per hectare for nitrogen and from 5 to 50 kg per hectare for phosphorous, with around 1/3 of this accumulating in the roots[51,52].

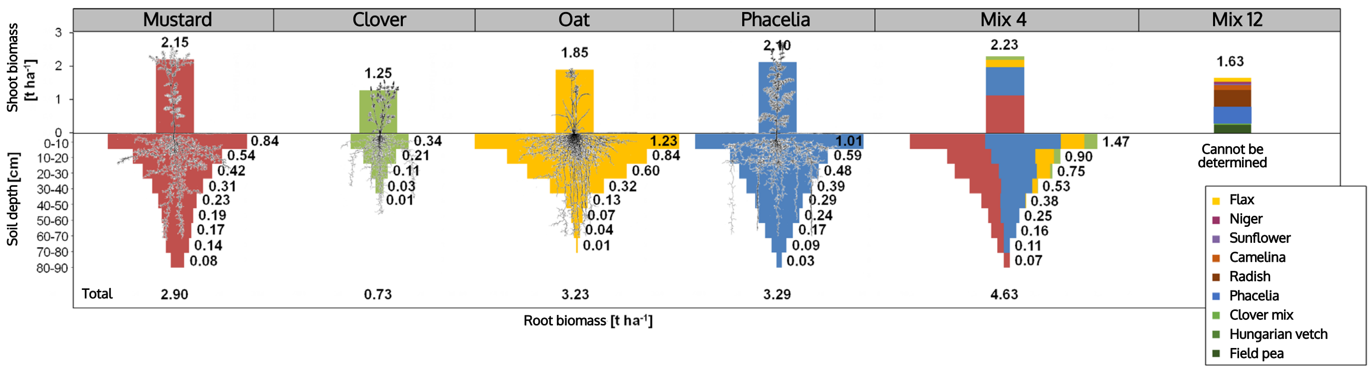


Fig. 6-1: Shoot and root biomass from the cover crops mustard (*Sinapis alba*), clover (*Trifolium alexandrinum*), bristle oat (*Avena strigosa*) and Phacelia (*Phacelia tanacetifolia*) sown alone, in the 4-crop mixture (Mix4) and in the 12-crop mixture (Mix12). The data used to create this graph was collected over four years (2015, 2016, 2017, 2019) at two sites (Asendorf, Lower Saxony and Triesdorf, Bavaria). The sowing was done between mid-August and the beginning of September. The graph shows the best linear, undistorted estimate for the respective biomasses (sample size = 24). Comment: For technical reasons, the root biomass from the 12-crop mixture could not be precisely recorded. The images of the crops were taken from Kutschera, Lichtenegger and Sobotik[7].

The nutrient accumulation is the product of the formed biomass and the nutrient concentration in the biomass. This means that a cover crop can effectively accumulate a nutrient if it has a high biomass content and shows a high ability to acquire this nutrient. For example, as a result of their ability to fix atmospheric nitrogen and the related processes, legumes typically contain high concentrations of nitrogen, iron and manganese[53]. Phacelia, Tartary buckwheat, turnip rape and radish all have high phosphorous and calcium uptake capacities and crucifers in general accumulate high amounts of sulphur and boron (Fig. 6-2)[54,55]. In a mixture containing different species of cover crop with different nutrient uptake potentials, overall more nutrients can be accumulated in the biomass when compared to cover crops sown individually (Fig. 6-2). This includes nutrients released from the decomposed preceding crop and nutrients extracted from the soil reserves. In any case, the uptake in the cover crop biomass offers the advantage that the nutrients are present in an organically-available form and can be better used than the nutrients stored in the soil by the subsequent crop once the cover crop has decomposed.

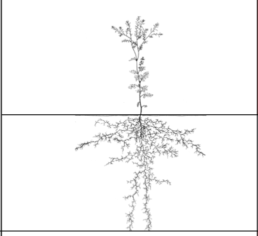
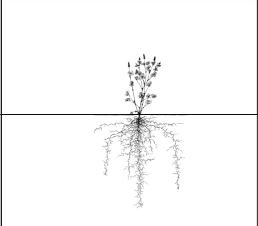
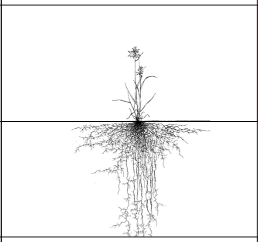
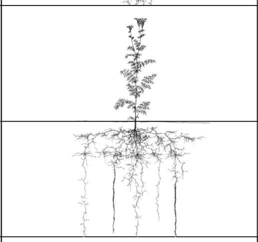
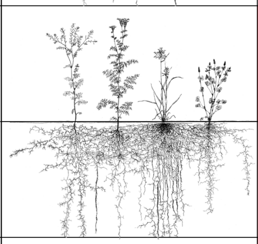
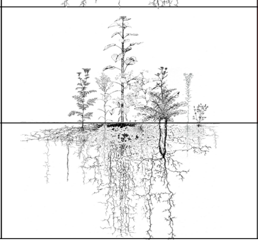
		Nutrient accumulation in shoots and roots [kg ha⁻¹]									
		Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sulphur	Iron	Manganese	Zinc	Boron
Mustard		51.3	8.1	68.2	44.2	5.0	11.7	0.6	0.09	0.13	0.04
		21.4	9.2	57.6	10.9	3.8	7.3	-	-	0.07	0.03
Clover		44.3	5.5	51.1	22.8	3.6	3.9	1.3	0.11	0.08	0.04
		22.5	3.4	21.8	3.4	2.4	1.9	-	-	0.05	0.02
Oat		49.7	9.9	78.9	14.1	3.8	5.7	1.2	0.22	0.07	0.01
		17.6	7.0	45.8	12.7	5.8	4.2	-	-	0.22	0.02
Phacelia		47.2	11.2	91.3	74.9	5.3	5.9	0.7	0.13	0.03	0.05
		21.9	14.2	97.0	20.7	4.0	4.7	-	-	0.06	0.04
Mix 4		55.8	11.4	90.0	55.0	5.3	9.0	0.9	0.13	0.11	0.05
		40.8	17.8	110.4	22.6	7.3	8.8	-	-	0.15	0.09
Mix 12		51.0	8.7	73.2	43.3	4.0	8.5	1.0	0.10	0.06	0.04
		-	-	-	-	-	-	-	-	-	-

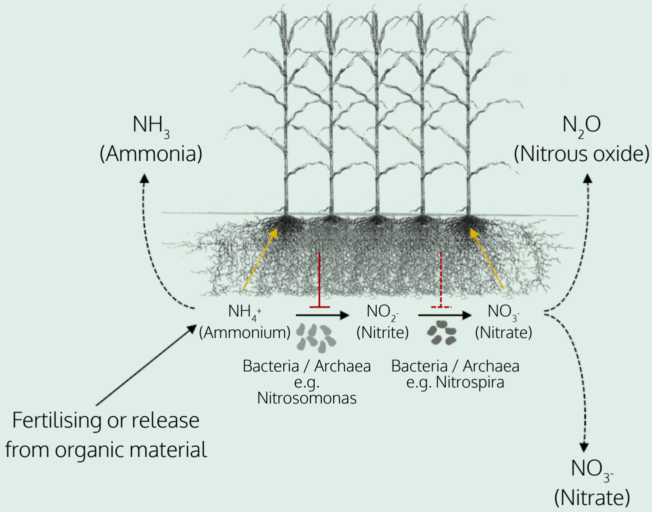
Fig. 6-2: Nutrient accumulation in the shoot and root biomass of different cover crops sown in pure stand and in mixtures. The data used to create this chart was collected over four years (2015, 2016, 2017, 2019) at two sites (Asendorf, Lower Saxony and Triesdorf, Bavaria). The sowing was done between mid-August and the beginning of September. It shows the best linear, undistorted estimate for the respective nutrient accumulation (sample size = 24). For the mixtures, the total value of all cover crop components is shown. The colour scale shows the highest value for each nutrient in red and lowest in white (note: the accumulation of iron and manganese in the roots could not be reliably determined due to technical difficulties. The accumulation of nutrients in the root biomass of the 12-crop mixture could not be quantified as the root biomass could not be determined). Crop diagrams were taken from Kutschera et al. (2009).

INFOBOX

EFFECTS OF BIOLOGICAL NITRIFICATION INHIBITORS

Nitrification is the microbial conversion of ammonium into nitrate. This process consists of four individual reactions where ammonium is first oxidised into nitrite, and then oxidised further into nitrate[69]. In well-aired arable soils, this process is very fast. Most arable soils therefore have 10-100 times more nitrate than ammonium[70], while crops in general prefer a mixed diet of ammonium and nitrate[71]. In the mid-20th century, very low nutrient losses in the form of nitrous oxide emissions and nitrate leaching were observed in natural stands of the tropical grass Brachiaria humidicola. At the same, very high ammonium concentrations were detected in the soil. Years later, this phenomenon was traced back to a very potent inhibitor, that restrains the oxidation of ammonium into nitrite[72]. Brachiaria humidicola releases this inhibitor into the soil via its roots and results in an increased amount of nitrogen in the form of ammonium in the soil. The positively-charged ammonium binds to negatively-charged soil particles and is therefore less at risk of being washed out than nitrate[73]. Biological nitrification inhibitors have also been detected in other grasses like Sudan grass, wheat, maize[49] and a range of other crop families such as crucifers[74], amaryllidaceae[75] and plantaginaceae[76].

The targeted use of main crops with a nitrification-inhibiting effect is something that is currently under discussion as this can help to reduce nitrogen losses in the form of nitrous oxide emissions and nitrate leaching during the vegetation phase[48]. Cover crops with nitrification-delaying properties are also currently being researched. In an ideal case, the formation of nitrate from the ammonium released from fertilisation and organic material in the soil should correspond to the crops' nitrate needs in terms of time and quantity[69]. The diagram below was taken from Kutschera et. al (2009)[7].



Infobox 6-1.

6.2 NUTRIENT CONSERVATION

When it comes to the uptake of nutrients in biomass, cover crops are an important element for reducing losses of residual nutrients from the preceding crop in comparison to fallow land that has not been greened[3,56]. However, there are clear differences when it comes to nutrient conservation in plant material over the winter. Cold-sensitive species, like niger, mostly die off in October[57]. As the crop material decomposes, all the nutrients absorbed up to that point gradually return to the soil. Even frost-sensitive plant species like white mustard, phacelia or bristle oat show a slower decomposition of the crop material at temperatures below 0°C. However, there are still some significant differences, as the results from the CATCHY trials show (see also Fig. 4-4). White mustard leaves decompose very quickly due to the low carbon to nitrogen ratios (C:N ratio of 10:5)[56], as the soil microorganisms have sufficient nitrogen available for each carbon atom to be converted. As a result, significant increases in the soil N_{min} contents occur just a few weeks after the first frosts. Over winter, the nitrogen can be stored in the subsoil and washed out into the groundwater[56,58]. Furthermore, white mustard shows high nitrogen outgassing losses compared to other cover crops[59]. All that remains after winter are mainly the difficult-to-decompose mustard stalks that have a very high C:N ratio (Tab. 6-1), which slow down the carbon conversion due to a lack of nitrogen. Less N_{min}

builds up under the dead crop material of the phacelia and bristle oat than under mustard, and almost no nitrogen leaching is observed until spring[60]. While bristle oat biomass seems to take longer to decompose (can be seen in the comparably low differences in the C:N ratio before and after winter; Tab. 6-1), a certain amount of the nitrogen released from the phacelia biomass seems to pass into the microbial biomass and is then protected from being shifted to the deeper layers of soil for a longer time (data not shown). Winter-hardy species like hairy vetch, crimson clover or Italian ryegrass can store significantly more nutrients in biomass over winter. One study[61] showed that, for example, the winter-hardy Landsberg mixture 50 % resulted in less N_{min} in the soils than under frost-sensitive cover crops. It can be useful to plant a combination of winter-hardy and frost-sensitive species, as early frost-sensitive species play an important role when it comes to ensuring a sufficient food supply for animals such as the common earthworm (Lumbricus terestris), for example, which are most active from September until the ground frost sets in. Species that continue to grow, however, can reabsorb the nutrients already released by the frost-sensitive species after the mineralisation begins and thus can protect them from leaching[58,61,62]. Winter-hardy cover crops are a good option for an efficient conservation of nutrients. However, is important to acknowledge, that if winter-hardy crops are used, additional measures to kill them off in spring are required[57]. Moreover, they can result in competing with the subsequent main crop for water. This will be covered in more detail in Chapter 8. In addition, nitrogen leaching, nitrogen losses in form of gas often occur when the cover crop is worked into the soil in spring. This is mostly seen when legumes are used[63,65]. A meta-study of over 106 individual studies[3] shows that the cultivation of cover crops does not lead to a significant increase in nitrous oxide emissions overall.

Table 6-1: C:N ratio in the shoot biomass of difference cover crops sown individually before and after winter 2021/2022 at the Asendorf site in Lower Saxony (sample size = 3).

COVER CROP SPECIES	C:N RATIO BEFORE WINTER	C:N RATION AFTER WINTER
White mustard	20.4	52.7
Egyptian clover	13.7	15.9
Bristle oat	23.0	30.4
Phacelia	24.6	42.9

6.3 NUTRIENT TRANSFER

Calculating the transfer of nutrients to the subsequent crop is one of the most important questions when evaluating nutrient management with cover crops. And it is actually one of the most difficult questions to answer. Different cover crops have different requirements in terms of nutrient provision depending on the time and quantity, so the aim is to use cover crops or cover crop mixtures that release nutrients in exactly the right quantities when the main crops have their highest nutrient requirements[41]. By selecting the right proportion of legumes, non-legumes, winter-hardy and frost-sensitive crops in the mixture, the speed at which the cover crop material decomposes can be adapted to the needs of the main crop.

Mixtures with species that are affected by frost early or species with lower C:N ratios are more likely to release nutrients than mixtures with higher proportions of winter-hardy species or species with higher C:N ratios. The latter are recommended, for example, before summer crops, which have their main nutrient requirements in the summer months.

Many studies approach the calculation of nutrient transfer by increasing the accumulation of a particular nutrient in the main crop compared to controls without a cover crop. With this method, it is clear that the use of cover crops on organically farmed land leads to an increase in nutrient accumulation in the main crop. In conventional agriculture, there is barely any nutritive effect on the main crop detected after a one-time use of cover crops. Often, even lower yields are recorded compared to the yields from land left fallow as a control since fertilised nutrients are immobilised in the soil to a certain extent when the cover crop residues are decomposing and are difficult for the main crop to access[3]. This particularly applies to cover crop residues with a high C:N ratio, while during the decomposition of legume cover crops with a higher proportion of nitrogen in the plant material, less of the applied fertiliser nitrogen is consumed by microorganisms. Thus, legumes pose less risk of yield reduction than non-legumes when compared to fallow land in conventional crop rotations[67].

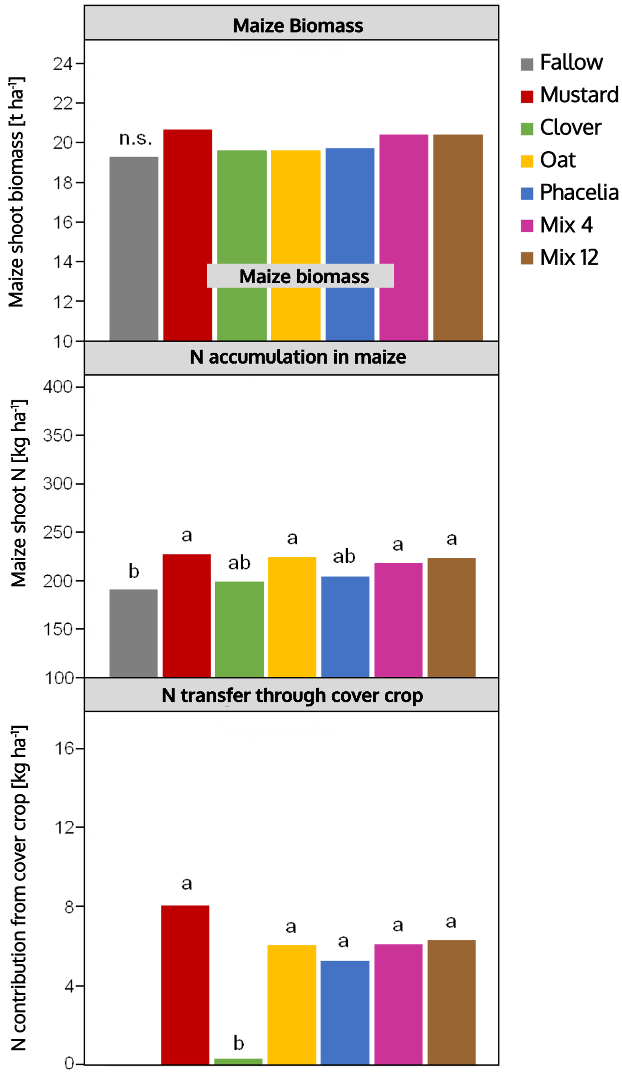


Fig. 6-3: Shoot biomass and nitrogen (N) accumulation in maize shoots and the transfer of nitrogen from the shoot biomass of the cover crop to the ripe maize. The data used in graphs was collected in 2018 in Asendorf, Lower Saxony and in 2019 in Triesdorf, Bavaria. The transfer of nitrogen from the cover crop to the maize was determined by means of nitrogen isotope marking (see Infobox 6-2). The graphs show the best linear, undistorted estimate for the respective parameters (sample size = 6-12). Different letters mark statistically significant differences according to Tukey's Test at $p < 0.05$. Note: the nitrogen transfers are only calculated on the basis of the cover crop shoot biomass and do not reflect the contribution of the nitrogen bound in the roots to the maize nutrition.

In the CATCHY trial, isotope marking (see Infobox 6-2) was used to determine that less than 5 % of the nitrogen accumulated in the cover crop shoot biomass reached the maize main crop in the following year (Fig. 6-3).
Therefore the nitrogen losses over winter (Fig. 4-4) could not explain the difference between the amount of nitrogen found in the cover crop in autumn and the final transfer to the main crop. Likewise, another study concluded that less than 10 % of the nitrogen absorbed by the cover crops in autumn was transferred directly to the wheat main crop in the following year. Rather, after the wheat harvest was still 26-60 % of the nitrogen from the cover crop available at a depth of 0-30 cm[68]. After the second or third integration of cover crops in the repeated wheat-cover crop-maize rotation in the CATCHY trial, which coincided with a reduced fertiliser application enforced since the amendment of the German Fertiliser Act (GFA) in 2017, an improvement in the nutrition of maize crops was detected (Fig. 6-4).

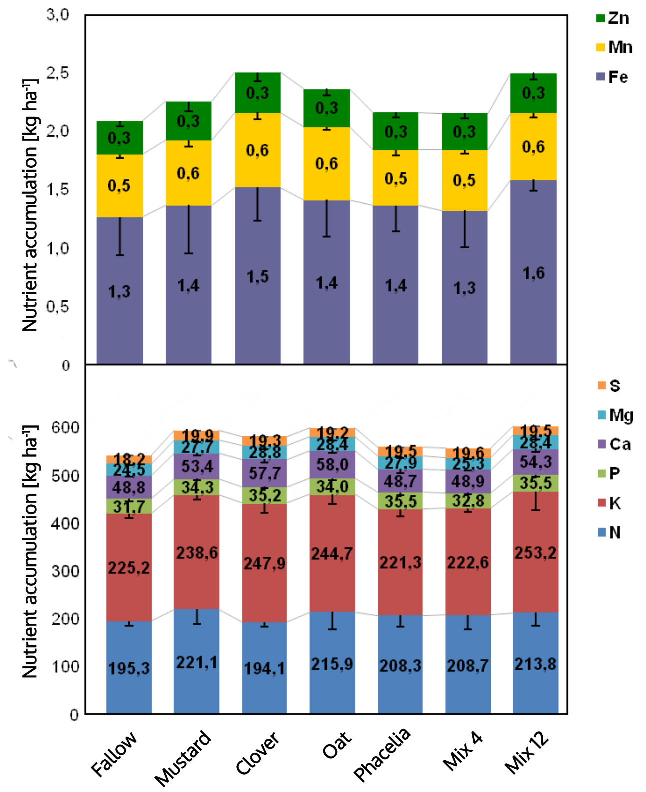
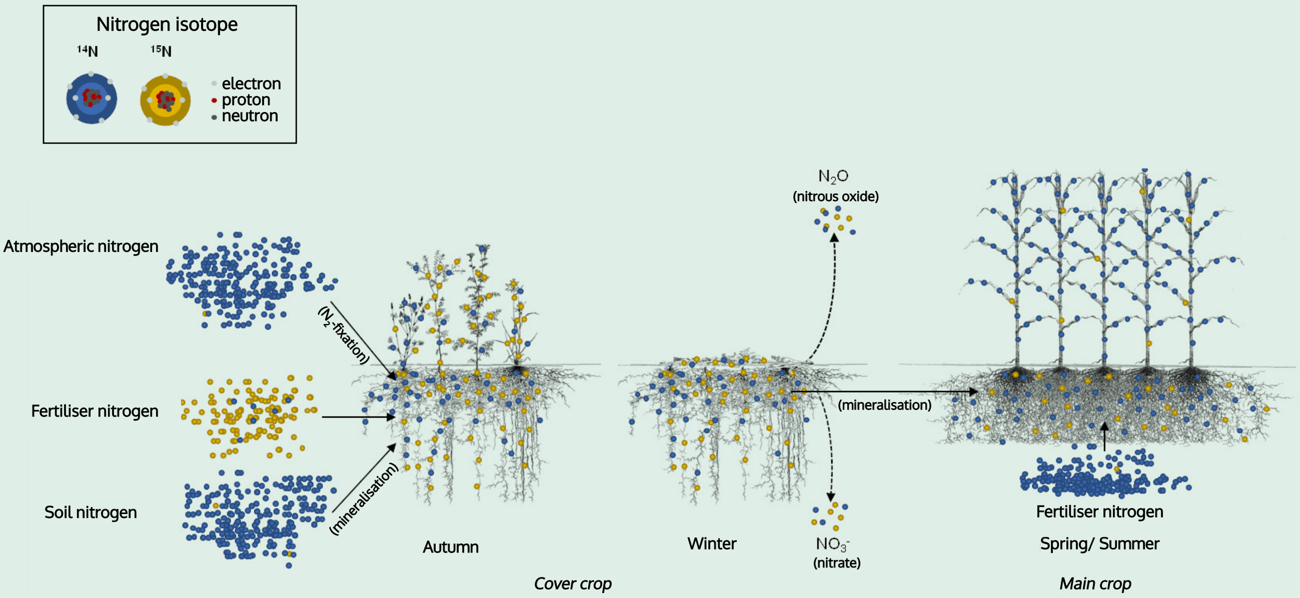


Fig. 6-4: Nutrient accumulation in the maize shoot biomass after the repeated integration of various cover crops in a repeating wheat-cover crop-maize crop rotation. The data used for these graphs was collected after the second (2019) and third (2020) integration of cover crops in the long-term rotation at the Asendorf site in Lower Saxony. They show the mean standard deviation (sample size = 9).

INFOBOX

THE PATH OF NITROGEN IN THE CROP ROTATION - QUANTIFIED BY THE DETECTION OF THE STABLE NITROGEN ISOTOPE ^{15}N



Isotope marking can be used to quantify the amount of nitrogen from the cover crop that actually reaches the main crop, and how much is immobilised in the soil or is lost from the decomposing cover crop material due to leaching or outgassing. Of course, the majority (> 99 %) of the nitrogen found in the air appear in form of stable isotope ^{14}N which has seven protons and seven neutrons in its nucleus. Just 0.366 % of the atmospheric nitrogen is present in the form of the equally stable isotope ^{15}N, which has an extra neutron in the nucleus. Under natural conditions, most of the nitrogen that is later absorbed by the crops is in the form of ^{14}N[77]. For the isotope marking method, cover crops are fertilised with nitrogen and then accumulate large quantities of the ^{15}N isotope. Mass spectrometry can then be used to determine the amount of this isotope in the crops' total nitrogen pool. This method takes advantage of the fact that the ^{15}N isotope is heavier than the ^{14}N isotope due to the additional neutron. Both isotopes can be separated in gas produced by burned crop samples and quantified separately[77]. This analysis can be used to determine how much nitrogen and with which ^{15}N marking intensity is in the cover crop material at the time of the maximum biomass formation as a starting value. Interestingly, in experiments like these legumes are often proven to have a lower ^{15}N marking intensity as they are less dependent on the absorption of nitrogen from the soil due to their ability to fixate nitrogen from the air. As such, legumes clearly accumulate more of the ^{14}N isotopes that occur naturally in the atmosphere than the ^{15}N isotopes that are experimentally applied with fertiliser[78].

Once the cover crops die off, for example with non-winter-hardy cover crops when the frost sets in, the crop material starts to decompose, and nitrogen can be released again. Soil and gas samples are then taken regularly, as are samples from the subsequent main crop, in order to measure the ^{15}N marking intensity. By knowing the marking intensity of the cover crop starting material and the marking intensity in the soil, gas, and main crop samples, we can quantify how much nitrogen flows into which compartments[77].

Infobox 6-2.

Interestingly, the reduced fertiliser use ensured an accumulation of higher quantities of nutrients in the main maize crop that had already effectively been taken up by the preceding cover crop. For example, white mustard resulted in the highest increase in nitrogen and sulphur accumulation, while Egyptian clover primarily encouraged an accumulation of trace elements (iron, copper, manganese) in the maize. It was also found that the species-rich cover crop mixture Mix12 encouraged the accumulation of all examined nutrients in the main crop. The results suggest that with the repeated cultivation of cover crops, the nitrogen application on maize could be reduced by 10-25 kg per hectare, which perfectly fits the guideline values of the German Fertiliser Act (GFA) of 10-40 kg per hectare. In a long-term experiment in Bavaria that took place over 36 years, researchers found that it was possible to save up to 51 kg of nitrogen per hectare of maize when legumes were regularly integrated into the crop rotation[8].

These results show that the long-term use of cover crops can result in significant savings potential when it is a matter of fertilising the subsequent main crop depending on the location and cover crop mixture used.

Legumes and their nitrogen input thus seem to play a key role. Recurring nutrient inputs result in organic nutrient deposits in the soil that the subsequent crop can draw on. This way, the subsequent crop not only benefits from the directly preceding cover crop, but from several cover crop cultivation phases. The effects of the cover crop are therefore widely distributed throughout the entire crop rotation.

INFOBOX

IN SHORT

- The nutrient acquisition of cover crops heavily depends on their species, location and management and is a product of the biomass formed and the nutrient concentration.
- Cover crop mixtures result in a more stable biomass formation and nutrient acquisition in different environments, although they do not exceed the yields from the best seeds sown individually in an environment.
- Mixtures result in very different nutrient accumulations depending on their composition. The mixture/composition should be chosen depending on the nutrient balance and release following the preceding main crop planted at the same location.
- Winter-hardy species are more effective at reducing nutrient losses over winter than frost-sensitive ones. The combination of winter-hardy and frost-sensitive species may be advisable as early frost-sensitive species can support soil life with nutrient inputs, while species that continue to grow over the colder months can absorb the nutrients that they release.
- The quantity and type of accumulated nutrients, as well as the decomposition properties of cover crops (freezing/frost tolerance, C:N ratio), are all decisive factors to ensure the transfer of nutrients to the subsequent crop. Thus, these parameters should fit the time and quantity of the actual nutrient requirements of the subsequent main crop (early release: early frost-sensitive species, low C:N ratio; late release: winter-hardy species, high C:N ratio).
- The positive effects on the subsequent crops are fewer in highly fertilised (intensively used) crop cultivation systems than in extensively used systems.
- The effects are not only visible in the subsequent main crop but instead work on/spread to the rest of the crop rotation.
- The long-term use of cover crops reduces fertiliser use as the recurring nutrient inputs in the soil result in organic nutrient deposits that the subsequent crops can draw on.

Infobox 6-3.

7. Effects on main crop yields

Robin Kümmerer

The effects of cover crop cultivation on the yields of the subsequent main crops can vary massively and depend on a wide range of interconnected factors that come into play at different times. The long-term influencing factors on the yield performance of main crops include the ability of cover crops to reduce the risk of erosion[79], to bind carbon in the soil and in the form of soil organic matter and thus build up a nutrient depot. Moreover, this counters the effects of anthropogenic climate change[80,81,82,102]. Significant yield reductions in agricultural production are predicted as a consequence of climate change, but this can be mitigated in the long term through the cultivation of cover crops[83,84]. The accumulation of soil organic matter in agricultural soils due to cover crop cultivation is a long-term process (see Chapter 4.1) that has a positive effect on the productivity of soils[85].

In the medium term, cover crop cultivation mainly influences factors that can be summarised by the term of "field hygiene". This refers to the crops' impact on weed populations, pests, and all types of pathogens. While cover crop cultivation has a largely positive impact on the long-term influence factors when compared to land that has been left fallow, with the last few factors mentioned it can also have negative effects on yields. A cover crop stand cannot only stand effectively suppress segetal flora, but will even reduce the soil seed bank[86,87,88]. However, under unfavourable conditions or if the cover crops are not grown properly (e.g. poor choice of species, insufficient establishment), the exact opposite of this can be the result. The situation is very similar with pests and pathogens[89]. The cultivation of cover crops can help to inhibit these, e.g. cover crops are often the only sensible option for tackling harmful nematodes[90]. Likewise, choosing the wrong cover crop species can encourage the spread of pathogens, for example clubroot in oilseed rape crop rotations[91]. Short-term effects of cover crop cultivation on the yield of the subsequent main crops can be achieved by influencing the soil structure, water and nutrient balance[92,93]. Both, positive and negative effects can occur. For example, if cover crops need more water for their growth than is provided by rainfall, the yield effect is clearly negative[94]. But if the right species and suitable sowing times are chosen, and if the cover crops are killed off at the right time, the water balance can be improved for the subsequent crops (see Chapter 9). Cover crops improve the nutrient content of soils as they take up, store, and remobilise the nutrients. The decomposition of difficult-to-mineralise cover crop litter can, however, result in an immobilisation of nitrogen and an undersupply in the main crop (see Chapter 4.2 and 6). A relatively new but intensively researched field is the microbiome at the plant-soil interface. The results from the CATCHY project show that this can also be influenced in the long term by the cultivation of cover crops. However, the vision of specifically influencing the microbiome through cover crops ("bioengineering") and thereby improving the yield and yield quality of agricultural crops still seems a long way off at present[103,104,105].

The variety of possible yield-influencing factors in cover crop cultivation and their complex interactions with location, weather and cultivation management make it difficult to assign the measured effects on yields to specific factors. Thus, the development of a prognosis as well as simple and general recommendations is still challenging. In the evaluation of scientific literature on cover crop cultivation before the planting of a maize as a main crop, a wide spectrum of yield effects was found. In 66 % of studies, results show that cover crops have a positive effect on silage or grain maize yields. Another 26 % show that cover crops have no effect on silage or grain maize yields. But 8 % of studies demonstrate that cover crops have a negative effect on yields, with yields that are on average 8 % lower than usual. Alongside the literature review, an evaluation of silage maize yields from almost 2,000 plots sampled in the CATCHY project was conducted. These plots only revealed an average of 0.8 % higher yields after cover crop cultivation. While this may seem disappointing at first, it actually means that the many advantages of cover crop cultivation can be utilised without resulting in any yield loss.

There is a wide variation in silage maize yields depending on which cover crop is used. This means that there is a certain degree of optimisation potential in cover crop cultivation only based on the species selection and mixture composition alone. In order to make the most of this potential, however, the responsible factors for the different yield effects must first be identified. In the CATCHY project, the annual factor, which is largely determined by the prevailing weather conditions (see Chapter 9), had a significant influence on the yield effects of the cover crops. Silage maize grown after a cover crop mixture produced a yield 1.1 % higher than silage maize grown after a single species of cover crop. A possible explanation for this is the legumes share in the cover crop mixture. In the literature, the C:N ratio of the cover crop biomass is often explained as an important factor for yield effects as it influences mineralisation rates[95,96]. Low C:N ratios, like those that occur with legumes due to the high protein contents, accelerate mineralisation. This means that the nutrients taken up by the cover crop are available to subsequent crops more rapidly when the cover crop biomass is terminated later. However, in the CATCHY project it was not possible to draw a general correlation between the yields, the nitrogen uptake, or the C:N ratio of the cover crop shoot mass and the yield of the subsequently planted silage maize. This could be due to the fact that despite the reduced fertilisation (see Chapter 1), the silage maize nutrient supply was not limited to an extent that the nutrient supplies from the cover crop biomass became a decisive factor. Ultimately, the C:N ratio is not the only variable that explains the nutrient supply from cover crops.

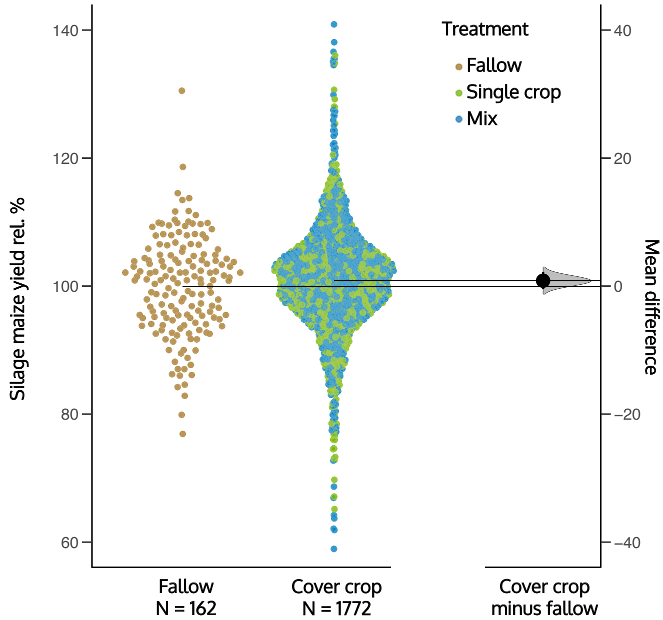


Fig. 7-1: Influence of cover crops, sown either alone or in a mixture, on the yield of the first subsequent silage maize crop in comparison to land left fallow at the Triesdorf and Asendorf sites from 2016 to 2022.

In most studies, the effects on the yield of the directly subsequent main crop are investigated rather than the effects on the crop rotation as a whole. For this reason, as part of the CATCHY project a long-term trial was designed. During this trial, the yields of the entire crop rotation were investigated to analyse the influence of repeated cover crop cultivation. In the long-term trial, the positive effect of the cover crops, and particularly cover crop mixtures, on the silage maize yield became visible over the years. On the contrary, the cultivation of cover crops before field beans tended to result in lower yields when compared to fallow land (this has not yet been scientifically proven). The legume-rich 12-crop mixture and clover sown alone showed the largest deficits. This could be an indication of yield-reducing effects due to legume fatigue. Interestingly, however, when winter wheat was planted after a cover crop as a second main crop, it seemed to benefit from the cover crop with yield increases of between 1 and 4 %.

This shows that the impact of crops on yields go beyond the first main crop. Moreover, there are temporal differences in the yield effects of the different species and mixtures investigated. While mustard proved to have the lowest yield-increasing effect on the silage maize, the same cannot be said for its effects on winter wheat. One reason for this could be a delayed mineralisation of the cover crop biomass. With lignified mustard stems, which have a high C:N ratio (see Table 6-1), nitrogen is initially depleted from the supply in the soil. If the C:N ratio in the soil or in the added crop residues is too high, it can make soil organisms less effective when it comes to the utilisation of organic matter. When there is limited nitrogen available in the soil, crops and microorganisms can end up competing for nitrogen that is quickly available. The result of this is a temporary fixation of nitrogen in microbial biomass and a decrease in the amount of nitrogen taken up by crops. Concerning winter wheat, the effect of the nitrogen fixation after a mustard cover crop is only temporary. As soon as the microbial decomposition processes overcome the point of the nitrogen limitation, nitrogen is once again provided for crop growth. Both mixtures show the advantages of combining different species of cover crops and also show the highest increase in yields for both main crops. In order to see the effects of the cover crops on yields even more precisely, the yields but also the yield components such as ear density and thousand kernel weight were analysed within the CATCHY project. It is therefore possible to see how the individual yield components of the main crop are influenced by different cover crops.

In addition to the different mineralisation profiles, other reasons for this could include the cover crops' different influences on the soil structure, water balance or release of biochemically active substances. It appears that when the tested species are combined in a cover crop mixture, there may be an overlapping of the yield-influencing effects, which could potentially result in a better overall performance of the mixture. Overall, it can be said that the cultivation of cover crops influences many of the yield factors of the subsequent crops in ways that cannot always be explained in detail. On average, the observed yield effects of cover crop cultivation are fairly low, which means that many other advantages of cover crop cultivation can be utilised without resulting in any loss of yield. By optimising the cover crop cultivation, the yield effects can be increased. The optimisation of the decomposition of biomass in cover crops seems to play an important role, e.g. through influencing the degree of lignification and the C:N ratios. This can be achieved by means of a farm- and location-specific cover crop cultivation management.

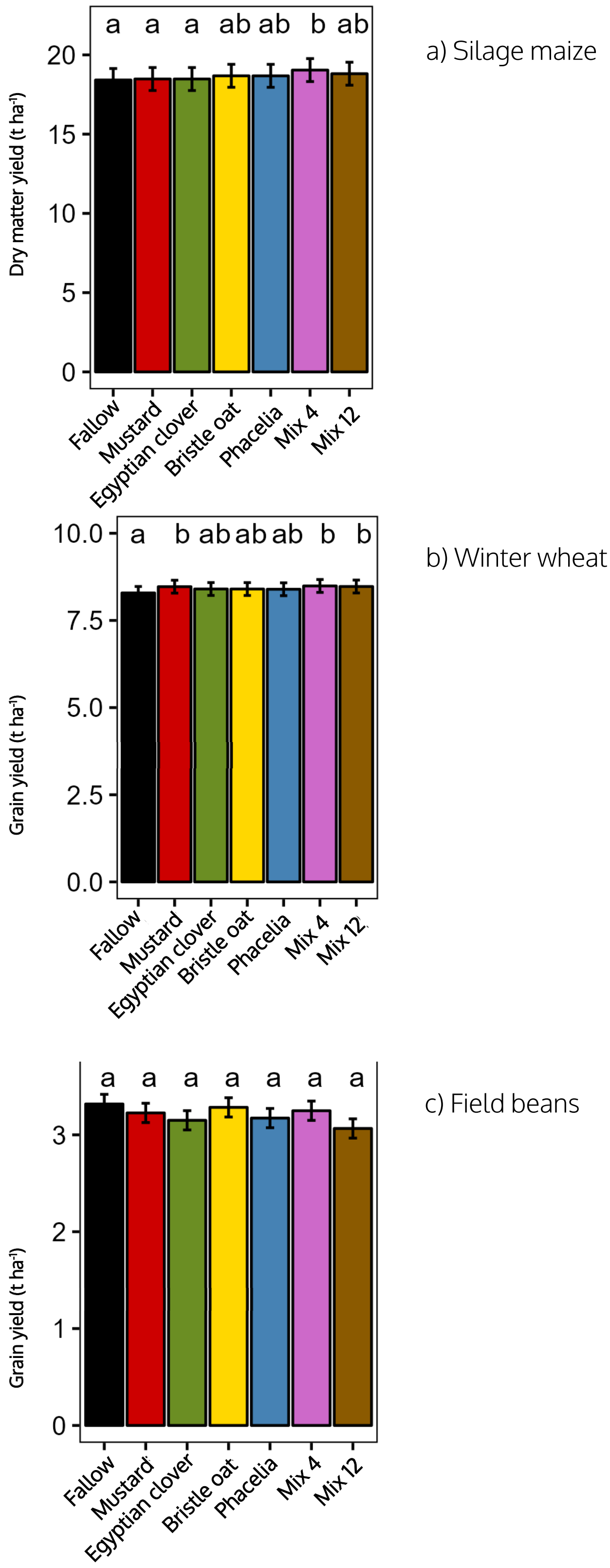


Fig. 7-2: Long-term yields (2016 to 2022) of a) silage maize, b) winter wheat, and c) field beans. Letters indicate significant differences.

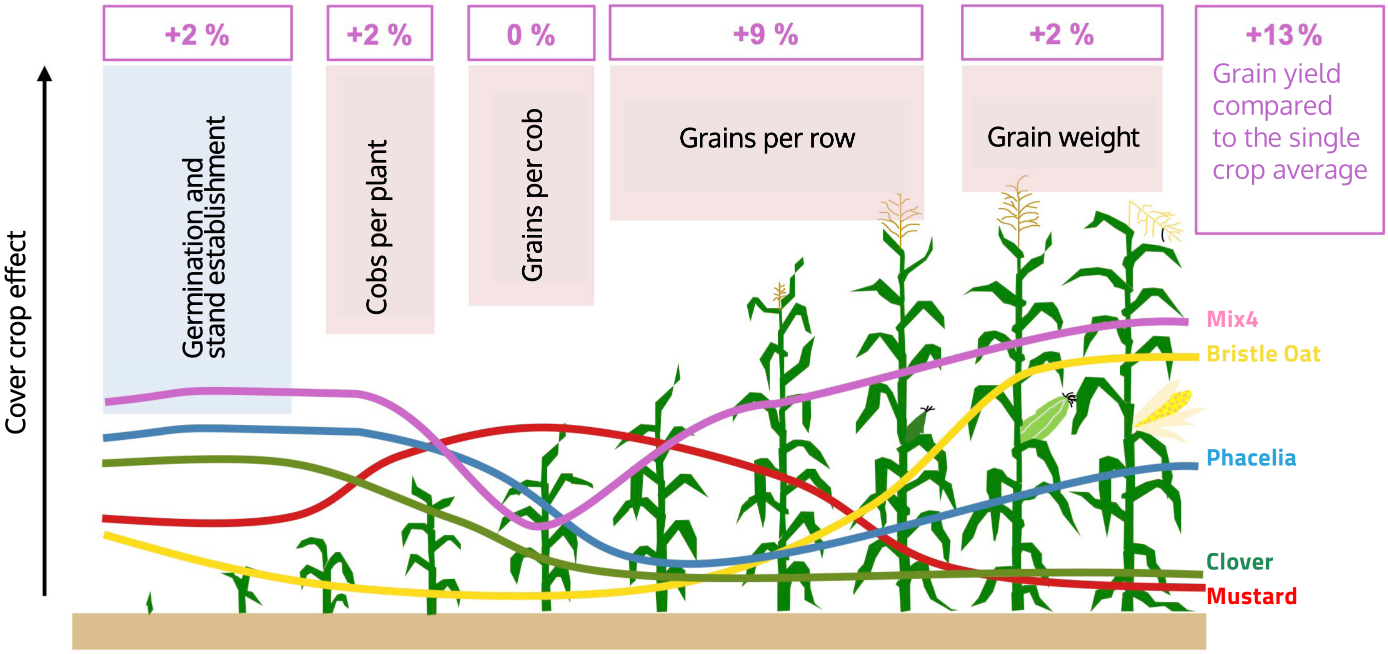


Fig. 7-3: Progression of the influences of different cover crops on the yields of subsequently cultivated silage maize over time.

INFOBOX

IN SHORT

- Cover crop cultivation can have various effects on main crop yields, but the positive effects dominate the negative ones in total. There is potential for yield optimisation through cover crop cultivation.
- Long-term yield factors include erosion protection, the sequestration of carbon in soils and the accumulation of nutrient-rich soil organic matter.
- In the medium-term, the cultivation of cover crops can influence weed populations, pests and pathogens.
- Short-term effects affect the soil structure and the water and nutrient balance.
- The choice of species and composition of cover crop mixtures can have an impact on the yields of the main crop.
- The analysis of the individual yield components gives some indication of the influence of cover crops on the yields over time.

Infobox 7-1.

8. Cover crop cultivation in times of climate change

Robin Kümmerer, Norman Gentsch, Diana Heuermann

In Germany, the effects of climate change vary significantly from region to region. Despite this, there are some general trends that can be observed in several different areas. Regional time series analyses and trends can be tracked on the German Meteorological Service website[97]. In general, levels of precipitation increase over winter and decrease over summer.

In large parts of Eastern Germany (Saxony, Saxony Anhalt, Brandenburg) in particular, spring precipitation is decreasing. This, combined with lower levels of precipitation in summer, is resulting in extended periods of drought. In Central Europe, extreme weather events are becoming much more common in late summer (heavy rainfall, extended periods of drought with high air temperatures). Periods of drought make it very difficult to establish cover crop growth. As such, cover crop cultivation strategies are now having to be adapted to these changes. Some of these establishment strategies will be presented in this chapter. The extension of the vegetation period and increasing lack of frost events will also impact the type of cover crop cultivation. The cultivation of cover crops can also reduce yield declines caused by environmental stress in the main crops. Due to the shift in precipitation to the winter months, there is an increased risk of nutrient leaching. Likewise, this shift in precipitation can lead to a destabilisation in the soil structure which has a negative impact on productivity of the crops grown, the need for intensive tilling and susceptibility to water erosion. Cover crop cultivation is an effective measure for combating these risks and it is particularly worth using as a tool when dealing with changing climatic conditions.

8.1 ESTABLISHMENT STRATEGIES

The monitoring of the optimal soil cultivation and sowing strategies under suitable conditions is becoming increasingly important when it comes to achieving a proper establishment of cover crops under difficult conditions. Due to precipitation deficits, the germination water is often insufficient, which is crucial for the establishment of the cover crops. Even in the event of a successful swelling and germination of the seeds a subsequent drying out of the seed horizon can result in the young seedlings dying off before their roots are able to access the water stored in the deeper layers of the soil. The results of this can range from an uneven field emergence to a total failure of the crop. Likewise, volunteer cereals cannot germinate under such conditions, although their germination is generally considered necessary by most agronomists for subsequent control measures. When the soils are remoistened, the resulting gaps in the cover crop stand end up being filled with volunteer crops, segetal flora and unwanted plants that grow from the germinated seeds that have been left behind (Fig. 8-2).

The key to a successful cover crop establishment is to design the sowing to ensure a rapid and safe starting development with a significant advantage over the segetal flora that grow in the same soil. Therefore, as much attention should be paid to the sowing of cover crops as to the sowing of the main crops. Under dry conditions, the choice of sowing time plays a decisive role. The soil must have sufficient moisture at the time of sowing and for a few days afterwards. In models, the number of days without rainfall after sowing is the most influential variable when it comes to the field emergence of cover crops[99]. It is important to wait for favourable conditions and not to sow too early. Periods of drought during growth can lead to an accelerated development of cover crop plants as this is how crops adapt to stressful situations.Usually they aim to produce offspring as quickly as possible to ensure the species' continuation. The results of this “emergency ripening” is exactly the opposite of what farmers usually aim for with cover crop cultivation: light, quickly ageing stands that form no biomass and stop vegetative growth after reaching the generative phase after only a short period of time. As such, the potential of an early sowing must be weighed up against the risk of drought and a later sowing date with lower temperatures, less hours of sunlight and a higher probability of precipitation.

The choice of tilling and sowing processes is initially based on the soil structure found (Fig. 8-1). If the soil structure is acceptable and there is no necessity of mechanically loosening compaction horizons or tracks created during spring or harvest, pre-harvest sowing or direct sowing techniques can be used (cf. Chapter 2). With these methods, the vegetation period of the cover crop can be maximised and the period of time that the fields are left fallow is minimised. These processes are only successful if there is enough germination water available. Under dry conditions the risk of a failed establishment is particularly high. Here, an early sowing date is automatically preferred and s. Thus, cover crop species that reach their generative phase later and are therefore suitable for early sowing dates, should be chosen. If the soil structure requires corrective measures in the form of tilling, more classic procedures like plough sowing or mulch sowing can be used. When sowing under dry conditions, it is important to wait for the next precipitation phase as this then allows for the processing and controlling of weeds and volunteer crops in order to ensure a secure establishment of the cover crop. In order to benefit from the conditions described above, a sowing date after mid-August is almost inevitable and thus species compatible with late sowing like phacelia or various crucifers should be used.

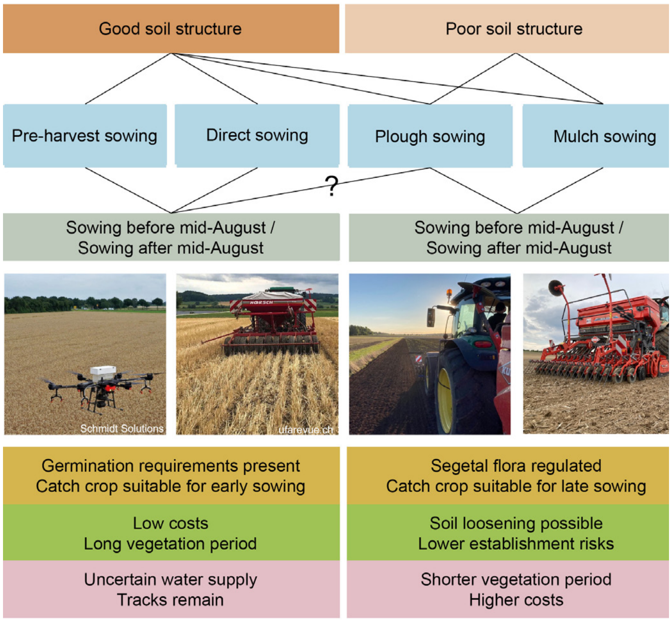


Fig. 8-1: Diagram of different establishment strategies for cover crops and their requirements (yellow), advantages (green) and disadvantages (red).

8.2 SELECTING SPECIES

It is often asked whether there are any species which are particularly suitable for the conditions described above. Essentially, all crops need water to germinate and grow, and even the most resistant species cannot establish themselves under certain conditions. Nevertheless, with the many species grown as cover crops in Central Europe, there are differences with regards to the optimal germination temperatures and germination water requirements. This was confirmed by a study that considered a wide range of species from different families and found out that the optimal germination temperatures are between 12°C and 37°C. Most species have relatively high germination temperatures, but phacelia and certain legumes have optimal and maximum germination temperatures in a lower range. Crucifers and grasses are particularly resistant to water shortages and manage to germinate even with lower water potentials[99]. These observations match the findings from the CATCHY trial.

When water is in scarce supply during plant growth periods, in addition to rapid soil cover to avoid unused evaporation, water use efficiency, i.e. the crops’ ability to form as much dry matter as possible from the available water, also plays an important role. Crops like mustard, sunflower or Tartary buckwheat all have a high degree of water use efficiency. With regards to soil coverage, significant differences between the investigated species were determined. Mustard and oil radish, both crucifers, cover the ground the fastest while Egyptian clover and field peas, both legumes, are much slower to cover the ground. By mixing oil radish and Egyptian clover, farmers can get both a quick and longer-lasting complete ground coverage.

8.3 FAILED ESTABLISHMENT

What can be done when all the advice was followed and every measure was taken, but the cover crop stand is still small, uneven, criss-crossed with tracks or interspersed with unwanted volunteer cereals, weeds and grasses?

If this occurs the following decision-making guidelines can be used. If the cover crop does not seem to be able to exert sufficient competitive pressure on the existing segetal flora, a change must be considered. Volunteer plants can shorten the, often already very tight, crop rotations and the seeds of weeds, such as Chenopodium album, take this opportunity to ripen and so significantly increase the weed potential for the subsequent main crops. The change should either be implemented as early as possible to allow for a new sowing with species that are compatible with later sowing or delayed as much as possible so that the land goes through winter as bare fallow. Care must be taken to ensure that the seeds of the segetal flowers are prevented from ripening.

If rollover tracks of agricultural machinery are visible in the cover crop stand, the extent of the compaction must be quantified. If there is still root activity in the compacted soil, or if the conditions for mechanical soil loosening are borderline, the cover crop stand should remain as it is.However, if no continiuous root penetration can be observed in the compacted zones and the soil can be tilled, loosening is recommended.

Fig. 8-2: Uneven cover crop stand with visible tracks and unsuppressed volunteer cereals (left). Poorly established cover crops do not suppress segetal flora and instead encourage their propagation (right).

INFOBOX

WHY DOES DROUGHT “STRESS” CROPS?

While they are growing, crops depend on a good supply of water. Even when they are in their seed stage, the presence of water is the most important trigger for their germination. The soaking of the seeds results in an interaction with the stored sugars, proteins and fats that provide the energy, enzymes and nutrients needed for important metabolic processes and ultimately germination. While young seedlings can draw on the seeds’ reserves for a while, the stable building of crop cells can only happen if there is enough water to create sufficient pressure inside the cells.

Once the seeds’ reserves have been exhausted, the crops then have to supply themselves. This can either happen through the uptake of nutrients from the soil or through the fixing of carbon dioxide from the air during photosynthesis. Both processes, however, require a sufficient supply of water. Many nutrients, including nitrogen, calcium, and magnesium, can only reach the roots via the mass flow that happens between the soil and the roots when the crops transpire water through the leaves. Other nutrients like phosphorous and potassium reach the root surface through diffusion processes, which can result in small differences in concentrations when they are taken up by the roots. These two mechanisms, mass flow and diffusion, are the main drivers of nutrient movement from the soil to the roots and are significantly restricted if the crops lack water[98]. In addition, mineralisation process in the soil work more slowly due to reduced microbial activity, which further restricts nutrient availability for plants. Water shortages can also negatively impact the photosynthesis process in two ways. Firstly, water is an irreplaceable starting material for energy transfer processes during photosynthesis reactions. And secondly, if crops do not get enough water they close their stomata and pause absorbing carbon dioxide. As such, crops that do not receive enough water also lack a sufficient amount of enough nutrients or energy. Crop symbiotes like bacteria and fungi also suffer from water shortages and often end up reducing their nutrient supply to the crops or their effects against crop pests.

Infobox 8-1.

8.4 EFFECTS ON YIELD

The advantages of cover crop cultivation for the yields of subsequent main crops were also investigated in a series of field trials as part of the CATCHY project. Various cover crops were integrated into a practical crop rotation and with maize being cultivated afterwards. The maize yields were measured and compared with maize yields that had been left fallow. In 2017 and 2021, when the maize experienced plenty of water while it was growing, there was no yield effect resulting from the cover crop cultivation observed. In 2018, 2019 and 2020, the maize crop struggled due to a lack of water, but due to the cover crops, the silage maize yield increased by 11 % on average compared to the maize yield on fields that had been left fallow.

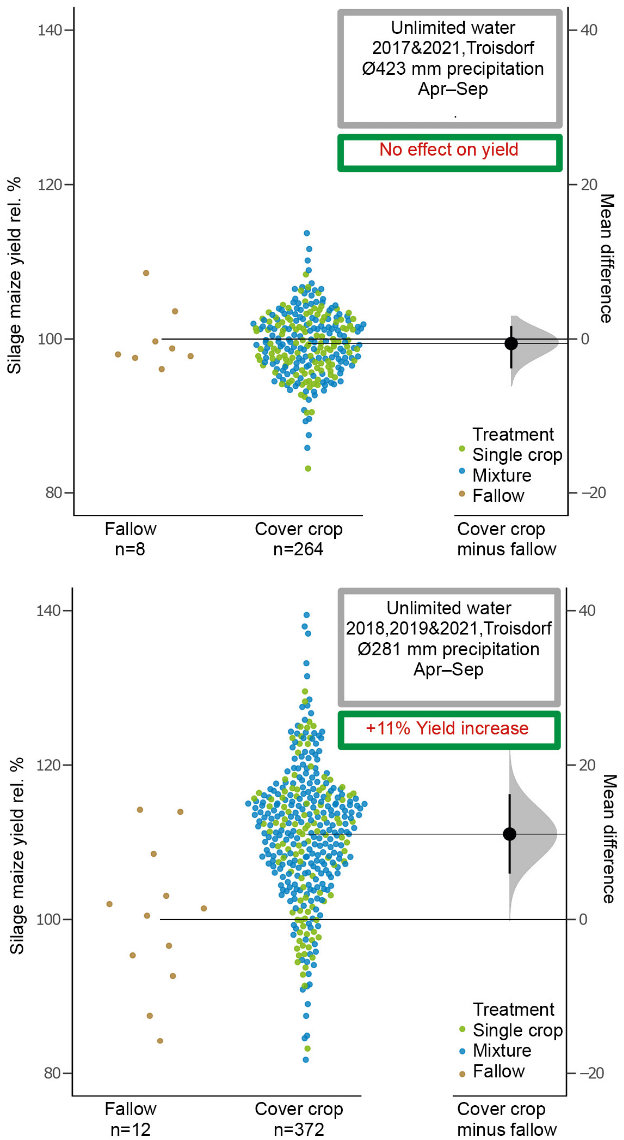


Fig. 8-3: Relative silage maize yield after the cultivation of different cover crops as a single crop and mixture compared to when grown on fallow land with unlimited water in 2017 and 2021 (top) and with limited water in 2018, 2019 and 2020 at the site in Triesdorf.

The wide variety of different species and mixtures used as cover crops shows the potential that still lies in the optimisation of the species selection and mixture composition (Fig. 8-3).

8.5 DO COVER CROPS COST WATER TO THE MAIN CROPS?

Unfortunately, there is not one simple answer to this question. Regional factors and annual climate variations make it difficult to build a uniform picture. The choice of cover crops, and whether they are winter hardy or frost sensitive, is a decisive factor.

At the site in Asendorf, the soil water balance was observed over a year from August 2018 to August 2019[56]. All the cover crops examined in the trial were not winter -hardy and the precipitation that fell over the entire period studied was 700 mm. The observations are depicted in Figure 8-4 and split into three phases. During the growth phase (Phase I), the cover crops require water from the soil and thus further reduce the soil's water storage more when compared to land that had been left fallow. On areas where cover crops are grown, water is mainly lost through transpiration as evaporation is kept to a minimum due to the crop coverage. But water losses still occur on fallow land, too. Evaporation is high due to the lack of soil coverage. As long as the climatic water balance (precipitation and evaporation) stays negative, there will be a continuous loss of water on fallow land and the water store in the soil will be depleted. In Figure 8-4, the shift from a negative to a positive water balance kicks off Phase II. The first overnight frosts set in at the beginning of December, the cover crops stop transpiration and gradually die off. The cover crop residues cover the ground as a layer of mulch, reducing evaporation. The levels of evaporation are higher on fallow land than on land where cover crops have been planted and the water store in the soil on fallow land fills up more slowly. By the beginning of February, the water storage in the soil on all cover crop areas exceeds that of fallow areas and remains high up until the maize is sown (mustard +4 %, clover +5 %, bristle oat +6 %, phacelia +12 %, Mix4 +14 %, Mix12 +9 %). Phase III begins after the cover crops are incorporated into the soil and the maize sowing starts. Throughout their entire growing period, the maize crops receive more water from the soils on land sown with cover crops than on land that has been left fallow. This is caused by the improved pore volume resulting from the root activity and the increased aggregate stability (see Chapter 4). The long-term use of cover crops thus leads to a better soil structure and an improved water retention capacity. An increased water retention capacity also reduces leachate losses. During periods of drought, the optimised water availability after cover crop cultivation is reflected in the improved main crop's yield (see previous section).

The transpiration capacities of the cover crop and the associated depletion of the water storage in the soil depend on the species and growth of the cover crop. The more biomass formed, the higher the transpiration losses. Other studies show that mustard, for example, has almost more than twice the transpiration capacity of crops like phacelia, vetch, or rye because it is capable of forming significantly more shoot mass[100]. Our results also showed the higher water consumption of mustard, as the lowest soil water contents at the end of the vegetation period were found in the soils where mustard was cultivated[56]. The investigated mixtures showed lower water losses in autumn than single crops. Possible reasons for this could be the improved microclimate near the soil surface and a lower evapotranspiration (evaporation + transpiration). With winter-hardy cover crops or a lack of frost, transpiration drops to a minimum in winter but then increases again in spring when photosynthetic activity picks up again. If there is not enough winter precipitation to compensate for transpiration losses, there is the risk of the soil water balance not being recharged sufficiently. With low levels of precipitation over winter and the risk of drought over spring, farmers can reduce biomass formation and transpiration rates by moving the sowing date and choosing suitable species of cover crops. Additional measures, such as rolling, mulching or the killing off of cover crops with herbicide, can also be taken to limit biomass growth and influence the soil water balance. However, it is important that the cover crop litter remains on the soil surface and is not worked into the soil. This is the only way to ensure that the mulching effect works properly, and that evaporation is reduced.

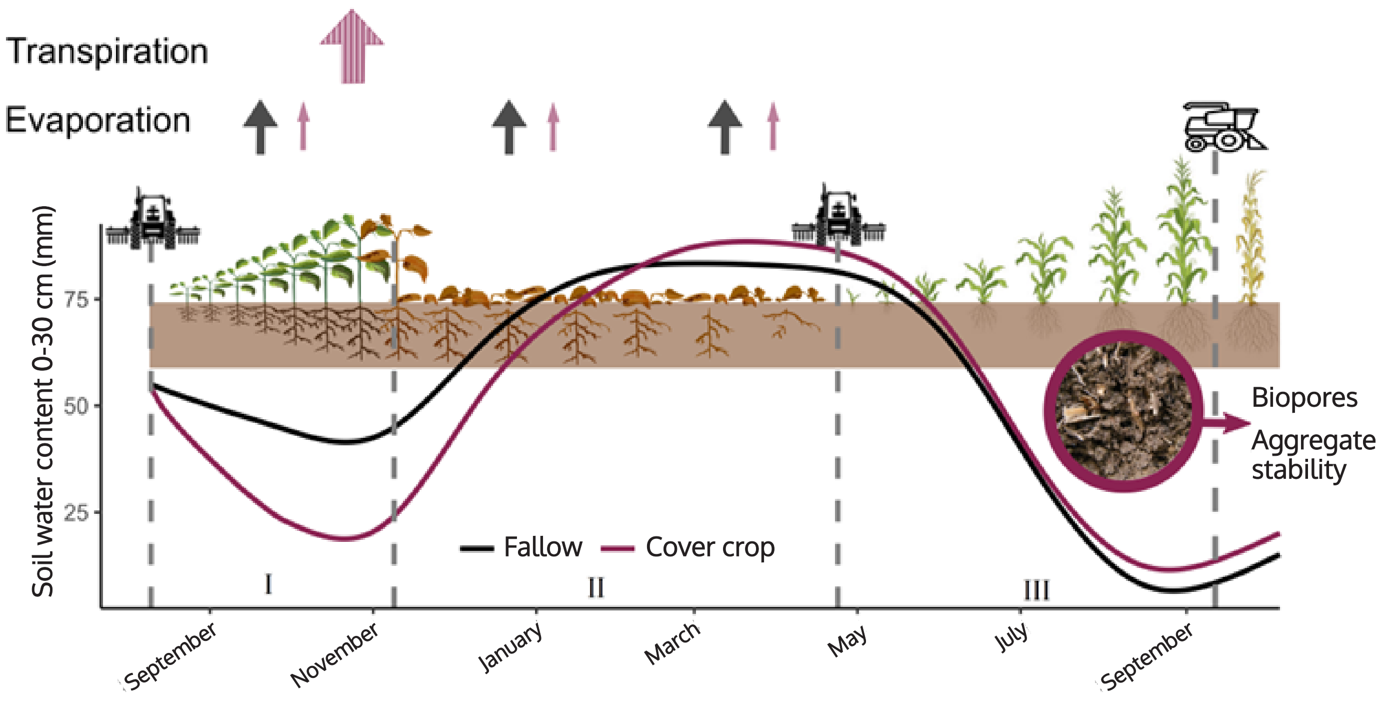


Fig. 8-4: The annual progression of the soil water balance from the cover crop sowing in 2018 to the harvest of the subsequent crop in 2019. The vertical lines (from left to right) mark the sowing of the cover crop in 2018, the dying off of the cover crop in 2018, the maize sowing in 2019 and the maize harvest in 2019. The annual progression on fallow land (black curve) is shown for comparison. The black and purple arrows show the main water loss paths for fallow land and land planted with cover crops.

9. When is cover crop cultivation profitable?

Jonas Schön, Peter Breunig

9.1 HOW CAN THE PROFITABILITY OF COVER CROP CULTIVATION BE CALCULATED ACCURATELY?

9.1.1 DIRECT AND LABOUR-FREE PERFORMANCE (DLFP)

This figure indicates the profitability of an agricultural production process by taking into account the performance and all direct and operating costs. The direct costs include costs for seeds, fertiliser, and plant protection products; the operating costs include fixed and variable costs for wages, services, machinery (depreciation, wear and repair costs, insurance, etc.) and operating materials. The direct and labour-free performance differs from the contribution margin because it includes fixed operating costs like the depreciation of machinery. This means that it can take into account the economic effects of changes in machinery use as a result of cover crop cultivation. The ownership structure, work equipment (own or third-party machinery) and employment regime (type of employment) are not included in this calculation. Likewise, the land costs, building costs and general costs of running a business are also not taken into account. Essentially, it considers all the relevant variables in order to accurately calculate the cost of an agricultural production process like cover crop cultivation.

9.1.2 PERFORMANCE OF A COVER CROP

Cover crop cultivation has many positive effects when it comes to climate, species, water, and soil protection. But only a few of these influencing factors are measurable and quantifiable. The extent of these effects is also strongly dependent on the species of the cover crop and the subsequent crop. The following four factors were defined through assumptions made based on literature reviews:

Increase in subsequent crop yields

- Cover crops increase the yield of the subsequent silage maize crop by 9 % due to a range of different influencing factors
- The increase in the subsequent crop yield can thus be classified as a positive effect of the cover crop
- Calculation:
  additional subsequent crop yield t DM/ha in percent * Market price of the subsequent crop €/t DM

Tab. 9-1: Calculation of the market revenue resulting from the additional yield from the subsequent silage maize crop.

CROP		COVER CROP
Additional yield	t/ha	1.7
Increase in yield	%	9
Price	€/t	138
Market revenue	**€/ha**	**234**

Nutrient supply to the subsequent crop (using nitrogen as an example)

- Cover crops reduce nutrient leaching over winter meaning that these nutrients are then available for the subsequent crop
- Legumes in a cover crop mixture can also help to fix nitrogen
- Both factors are multiplied by the price of nitrogen and represent a credit in the form of nitrogen fertiliser savings
- Calculation: - kg N * € /kg N

Tab. 9-2: Calculation of the performance based on the nutrient supply to the subsequent silage maize crop.

N input	kg/ha	-60
N price	€/kg	2.60
N costs	**€/ha**	**-156**

Carbon sequestration

- The content of the soil organic matter in the soil can be increased through crop growth and greening, and around 1.8 t CO_2/ha in the form of carbon is stored in the soil annually
- In order to maintain a safety margin in the event of a drop in the amount of carbon stored in the soil, 30 % of the bound carbon is retained as a buffer
- The amount of CO_2 bound in the soil is multiplied by the price of €30 per t CO_2 and the safety margin and attributed to the market performance
- Calculation: t CO_2/ ha * (1-0.30) * € / t CO_2
- In order to preserve the aspect of additionality here, this performance is only credited to the area of cover crops grown in addition to the obligations under the CAP23 and the German Fertiliser Act (GFA)

Tab. 9-3: Calculation of the performance based on participation in carbon farming initiatives

CARBON SEQUESTRATION	t CO_2/ha	1,8
Safety margin	%	30
CO_2 price	€/t CO_2	30
Revenue	**€/ha**	**38**

Value of above-ground biomass

- The cover crop vegetation can be harvested once
- The harvesting has barely any impact on the carbon sequestration in the soils, the nutrient supply for the subsequent crop, however, remains absent and so the yield of the subsequent crop is reduced
- Calculation: Harvested quantity in t DM /ha * Market price €/t DM

Tab. 9-4: Calculation of market value based on the harvest of the above-ground biomass

COVER CROP YIELD	t/ha	5
Price	€/t	125
Market revenue	**€/ha**	**600**

9.1.3 COSTS OF A COVER CROP

The cultivation of cover crops results in not only a range of benefits, but also several costs. The costs for the establishment are easy to quantify, but there are also influencing factors that are more difficult to quantify. This includes, for example, additional, chemical plant protection for killing off the cover crops and additional herbicide use on the subsequent crop. As these costs depend on the cover crop species, the subsequent crop and the farm management, they are not taken into consideration in the calculation shown. Three cost elements are taken into account for the profitability calculation:

The increased nutrient requirements for the additional yield

- The additional yield of the subsequent crop leads to higher nutrient removals which means that additional fertiliser is needed
- The additional nitrogen, phosphorous and potassium requirements due to the additional calculated yield is multiplied by the removal values and the nutrient prices and added to the fertiliser costs
- Calculation:
  % additional yield * t/ha yield * N, P, K removal factor * €/kg N, P, K

Tab. 9-5: Calculation of the additional fertiliser costs due to the additional yield of the subsequent silage maize crop using the removal factors.

ADDITIONAL YIELD	t/ha	5,4	ADDITIONAL YIELD	t/ha	5,4	ADDITIONAL YIELD	t/ha	5,4
N removal factor	kg/t	4.3	P removal factor	kg/t	1.6	K removal factor	kg/t	5.10
N amount	kg/ha	23.22	P amount	kg/ha	8.64	K amount	kg/ha	27.54
N price	€/kg	2.6	P price	%/kg	1.2	K price	€/kg	1.50
N costs	**€/ha**	**60.37**	**P costs**	**€/ha**	**10.37**	**K costs**	**€/ha**	**41.31**

Seed costs

- The quantity of the required seeds must be multiplied by the price of the seeds and the seed costs allocated.
- Calculation: kg/ha * €/kg

Tab. 9-6: Calculation of the seed costs for cover crop cultivation.

Seed quantity	kg/ha	25
Price	€/kg	2.50
Seed costs	**€/ha**	**63**

Additional operating costs (wages, machinery, diesel)

- Cover crop cultivation costs
- The required working hours, machinery use and fuel consumption for additional tilling and sowing with seed drills in autumn is multiplied by the relevant costs and allocated to the operating costs
- Calculation: wh*€/h + l/h*€/l + material costs/ha

Tab. 9-7: Calculation of the operating costs for establishing the cover crop.

Working hours (wh)	h/ha	3.7
Hourly wage	€/h	19
Wages	€/ha	70
Fuel requirements	l/ha	40
Fuel price	€/l	1.20
Fuel costs	€/ha	48
Operating costs	€/ha	44

9.1.4 SPREAD OF THE INFLUENCING FACTORS

The factors mentioned above that are used to calculate the profitability of cover crop cultivation are subject to a certain range. The stated values correspond to current average values but can vary significantly from farm to farm and depending on the weather. The following table shows the ranges of the individual influencing factors.

Tab. 9-8: Spread of influencing factors used for the profitability calculation.

INFLUENCING FACTOR	MIN	MAX	UNIT
Increase in subsequent crop yields	-5.00	15.00	%
Market price for silage	80.00	140.00	€/t
Nitrogen supply for the subsequent crop	30.00	60.00	kg N/ha
Nitrogen price	0.65	2.80	€/kg
Carbon sequestration	0.80	1.70	t CO_2/ha
Cover crop yield	3.00	8.00	t TM/ha
Phosphorus price	0.50	1.30	€/kg
Potassium price	0.55	1.50	€/kg
Seed costs	25.00	125.00	€/ha
Fuel price	0.80	1.60	€/l

The increase in the subsequent crop yield has a very wide range and can also have a negative impact. In wet years, there is barely any or no increase in yield in comparison to fallow areas, but in dry years the increase is more pronounced. The tilling carried out before planting the main crop also plays an important role. If this is done when conditions are too wet or if it is not done in water-conserving process in dry years, the yield can be negatively affected.

The market prices for silage depends on cereal prices and can vary massively from region to region.

The nitrogen supply from the cover crop to the subsequent crop is subject to many influencing factors (see Chapter 6). For one, the composition of the cover crop has a major influence. Legumes play an important role in binding nitrogen. Grasses and other winter-hardy components can also take up the available nutrients in autumn, store them, in the biomass and protect them from leaching. The time of the cover crop's death off and the time that the tilling is carried out in spring also have an impact. At this point the mineralisation of the cover crop residues takes place and thus the release of the contained nitrogen is initiated. Therefore, the tilling should not be carried out too early depending on the cover crop and the subsequent crop. The nitrogen supply can also vary depending on the weather. If a lot of precipitation takes place, there is a risk of nutrients leaching in the deeper soil layers. This means that the nutrients will no longer be available to the crops. With lower soil temperatures, the nitrogen mineralisation is delayed and nutrients only become available later or with the second subsequent crop. The time at which the stored nitrogen becomes available also depends on the C:N ratio of the cover crop - the more lignified a cover crop is, the longer the mineralisation takes.

Prices for nitrogen, phosphorous and potassium are subject to stock exchange prices for nutrients and can vary accordingly.

- The formation of soil organic matter and sequestration of carbon in the soil takes place when the crops bind carbon from the air during photosynthesis (see Chapter 5). The longer the vegetation period and the higher the photosynthesis rate of the cover crop, the more carbon can be sequestered. Grasses typically bind more carbon than legumes, for example. Still, it is important to remember that carbon is lost whenever the soil is tilled. The stated values already include a buffer of 30 %. The costs of cover crop seeds vary significantly. For example, legumes and grasses for harvesting are at the top end of the price range. Finally, the fuel costs depend on crude oil prices which are also subject to massive variations.

9.2 PROFITABILITY OF COVER CROP CULTIVATION ON TYPICAL FARMS IN SOUTHERN GERMANY

As part of the CATCHY project, "typical farms" were established according to agri benchmark's Standard Operating Procedure[101] in order to calculate the profitability of cover crop cultivation. agri benchmark is a global non-profit network of agricultural economists, consultants, producers, and specialists in key sectors along the added value chain. The network uses international standardised methods to analyse farms, production systems and their profitability.

Each typical farm consists of a data set that describes the farm in detail. A typical farm is based in a defined region, has a set of factors that are typical of this region (land, work, capital) and implements production systems that are typical of the region.

In a joint group discussion with farmers, expert consultants, and partners from the scientific community, the following three typical farms for southern Germany were developed:

Lower Franconia - Arable farm

- 240 ha arable land
- Crop rotation: winter wheat - cover crop - fodder beet - winter wheat - silage maize/soybean/summer barley
- 30 % of the land in red and yellow areas

Middle Franconia - Dairy farm with a biogas plant

- 160 ha arable land
- Crop rotation: silage maize - winter wheat/triticale - cover crop - silage maize - winter barley - cover crop
- 60 % of the land in red and yellow areas

Upper Palatinate - Dairy farm

- 110 ha arable land
- Crop rotation: spelt/winter wheat - cover crop
- - silage maize - winter wheat - winter barley/field peas - winter oilseed rape
- 25 % of the land in red and yellow areas

9.3 POTENTIAL FOR INCREASING PROFITABILITY BY EXPANDING COVER CROP CULTIVATION

The calculation of profitability is divided into the following four levels:

Level 1: CURRENT state

- Cover crop cultivation corresponds to the legal minimum according to the CAP23 and the German Fertiliser Act (GFA)

Level 2: Maximum cover crop cultivation

- Cover crop cultivation corresponds to the maximum crop cultivation possible

Level 3: Maximum plus carbon farming

- Like Level 2, but includes the economic effects of participation in private-sector carbon farming initiatives

Level 4: Maximum plus carbon farming plus use of growth

Like Level 3, but includes the economic effects secured by using the above-ground biomass

According to the CAP23, a maximum of 20 % of arable land should be left fallow over winter. If the proportion of summer crops exceeds 20 %, it is important to note that these areas must be greened over winter. With our calculation, this greening is covered by the cultivation of cover crops. According to the German Fertiliser Act (GFA), but with a few exceptions for red or yellow areas, a cover crop must be planted before each summer crop that is to be fertilised with nitrogen (red area) or phosphorus (yellow area). These guidelines are taken into account for all four levels in view of the proportion of red and yellow areas on the typical farms.

9.3.1 ASSUMPTIONS FOR THE CALCULATIONS

When legumes are used as subsequent crop after a cover crop, it is assumed that there are no legumes in the cover crop mixture which means that no nitrogen can be fixed, thus reduces the nutrient supply from the cover crop by 30 kg / ha N.

For both Level 3 and Level 2, it is assumed that a cover crop is planted before each summer crop. It is also assumed that the cover crop areas cultivated in addition to those covered in Level 1, are included in private-sector carbon farming initiatives. Carbon is added to the soil through the vegetation of the areas over winter and the subsequent green fertilising (see Chapter 5). This method draws carbon from the atmosphere and stores it as soil organic matter in the soil. The accumulation of soil carbon in agricultural land is referred to as carbon farming. Private certification companies can generate CO_2 certificates based on the sequestration of carbon in the soil that companies or private individuals can purchase to offset their CO_2 emissions. Participation in carbon farming initiatives with verified standards is subject to strict criteria. In order to qualify for additionality, only the area of cover crops grown in addition to the area already required by law is counted. As such, farms cannot participate with just the cover crop cultivation area from Level 1.

The removal of above-ground biomass at Level 4 leads to a lower yield from the subsequent crop due to delayed sowing and a lack of water. As no removal fertilisation takes place for the harvested biomass, it is assumed that this cover crop does not supply the subsequent crop with additional nutrients. Due to the reduction in yield, the main crop requires fewer nutrients compared to the other levels which means that less money has to be spent on fertiliser. The market price for above-ground biomass is ex-field, which means that this process does not incur any additional operating costs.

9.4 RESULTS

9.4.1 LOWER FRANCONIA - ARABLE FARM

The following table shows the profitability of cover crop cultivation before silage maize on the typical farm for the Lower Franconia region per hectare for each of the four levels.

Tab. 9-9: Calculation of the performance minus direct and operating costs for cover crop cultivation before silage maize for each of the four levels on the farm in Lower Franconia.

		LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	UNIT
Additional yield		1.7	1.7	1.7	-2.9	t/ha
Increase in subsequent crop yield		9.0 %	9.0 %	9.0 %	-15.0 %	%
Producer price		138	138	138	138	€/t
Cover crop yield					5	t/ha
Producer price					125	€/t
Carbon sequestration				1.26	1.26	t CO_2/ha
CO_2 price				30	30	€/t CO_2
Market performance		**238**	**238**	**275**	**242**	**€/ha**
Seed costs		63	63	63	120	€/ha
N input for additional yield		23	23	23	-39	kg/ha
N supply from cover crop		-60	-60	-60	0	kg/ha
N costs	2.60	-96	-96	-96	-101	€/ha
P input for additional yield		9	9	9	-14	kg/ha
P costs	1.20	10	10	10	-17	€/ha
K input for additional yield		28	28	28	-46	kg/ha

K costs	1.50	41	41	41	-69	€/ha
Fertiliser costs		-44	-44	-44	-187	€/ha
Direct costs		**19**	**19**	**19**	**-67**	**€/ha**
Wages		70	70	70	70	€/ha
Machinery costs		44	44	44	44	€/ha
Diesel costs		48	48	48	48	€/ha
Operating costs		162	162	162	162	€/ha
Performance minus direct and operating costs		**56**	**56**	**94**	**147**	**€/ha**

With an additional market price of € 238/ha, the additional subsequent crop yield has the largest positive impact on the profitability of the cover crop cultivation. But the nutrient supply to the subsequent crop also significantly reduces direct costs by € 156/ha given the assumed high fertiliser prices. As harvesting the above-ground biomass has a negative impact on the yield and does not supply nutrients to the subsequent crop, performance is reduced. But thanks to the proceeds from the sale of fodder and reduced fertiliser requirements, this scenario ultimately has a positive impact on the performance minus direct and operating costs. At € 38/ha, participation in carbon farming initiatives also has a very positive effect on the profitability of the cover crop cultivation. However, it is important to remember that due to the additionality only 40 % of the cultivated area can be included in these initiatives. The performance minus direct and operating costs of cover crops when followed by silage maize is in the very positive range (from € 56/ha to € 147/ha) for all four scenarios. When looking at the crop rotation as a whole calculated for the entire cultivated area, the following results are produced:

Tab. 9-10: Calculation of the cover crop cultivation for the entire crop rotation and total cultivation area on the Lower Franconia farm.

PERFORMANCE MINUS DIRECT AND OPERATING COSTS FOR COVER CROPS	PER ha	PER OPERATION	TOTAL PERFORMANCE MINUS DIRECT AND OPERATING COSTS	DIFFERENCE IN PERFORMANCE MINUS DIRECT AND OPERATING COSTS	COVER CROP AREA
Level 1	70.44 €	4,764.56 €	367,846.55 €	- €	72
Level 2	70.44 €	9,990.64 €	373,072.63 €	5,226.08 €	120
Level 3	78.00 €	11,805.04 €	374,887.03 €	7,040.48 €	120
Level 4	86.07 €	12,449.88 €	375,531.87 €	7,685.32 €	120

With Level 1 and 2, the average performance minus direct and operating costs per hectare is identical. When looking at the farm as a whole, the performance minus direct and operating costs of the cover crops increases when the cultivation is expanded from 72 ha to 120 ha, rising from € 5,226.08 to € 9,991.64. Compared to the table above, the actual performance minus direct and operating costs per hectare at Level 3 and 4 decreases as due to the additional only 40 % of the cover crop cultivation area can be included in the carbon farming initiatives. When looking at the results overall, participation in carbon farming initiatives increases the performance minus direct and operating costs by € 1,814 compared to Level 2. In this crop rotation, the cover crop harvesting can only be done before the silage maize and soybeans due to the sowing time of the subsequent crop. The average performance minus direct and operating costs per hectare increases to € 86.07/ha.

Tab. 9-11: Calculation of the direct and labour-free performance for the cover crop cultivation before the silage maize for each of the four levels on the farm in Middle Franconia.

		LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	UNIT
Additional yield		1.4	1.4	1.4	-2.4	t/ha
Increase in subsequent crop yield		9.0 %	9.0 %	9.0 %	-15.0 %	%
Producer price		138	138	138	138	€/t
Cover crop yield					5	t/ha
Producer price					125	€/t
Carbon sequestration				1.26	1.26	t CO_2/ha
CO_2 price				30	30	€/t CO_2
Market performance		**198**	**198**	**236**	**308**	**€/ha**
Seed costs		63	63	63	120	€/ha
N input for additional yield		19	19	19	-32	kg/ha
N supply from cover crop		-60	-60	-60	0	kg/ha
N costs	2.60	-106	-106	-106	-83	€/ha
P input for additional yield		7	7	7	-12	kg/ha
P costs	1.50	11	11	11	-18	€/ha
K input for additional yield		23	23	23	-38	kg/ha
K costs	1.20	28	28	28	-46	€/ha
Fertiliser costs		-67	-67	-67	-147	€/ha
Direct costs		**-4**	**-4**	**-4**	**-27**	**€/ha**
Wages		85	85	85	85	€/ha
Machinery costs		73	73	73	73	€/ha
Diesel costs		48	48	48	48	€/ha
Operating costs		**206**	**206**	**206**	**206**	**€/ha**
Performance minus direct and operating costs		**-4**	**-4**	**34**	**129**	**€/ha**

9.4.2 MIDDLE FRANCONIA - DAIRY FARM WITH BIOGAS PLANT

Due to a slightly lower silage maize yield in comparison to the farm in Lower Franconia, the market performance of the farm in Middle Franconia is slightly lower at € 198/ha due to the increase in the subsequent crop yield. In view of the lower additional yield, however, fewer nutrients need supplying in the form of fertiliser which means that fertiliser costs and the total direct costs decrease to - € 4/ha at Level 1 to 3 and - € 27/ha at Level 4. At € 206/ha, the operating costs are significantly higher than on the farm in Lower Franconia. This is partly due to the higher wage costs that are the result of more time being spent on cultivation due to smaller area structures and different economic practices, and partly because of the higher machinery costs that result from the more modern fleet.

Tab. 9-12: Calculation of the cover crop cultivation for the entire crop rotation and total cultivation area on the Middle Franconia farm.

PERFORMANCE MINUS DIRECT AND OPERATING COSTS FOR COVER CROPS	PER ha	PER OPERATION	TOTAL PERFORMANCE MINUS DIRECT AND OPERATING COSTS	DIFFERENCE IN PERFORMANCE MINUS DIRECT AND OPERATING COSTS	COVER CROP AREA
Level 1	**- 3.65 €**	**- 175.20 €**	52,576.80 €	**- €**	48
Level 2	**- 3.65 €**	**- 292.00 €**	52,460.00 €	**- 116.80 €**	80
Level 3	11.47 €	917.60 €	53,669.60 €	1,092.80 €	80
Level 4	106.87 €	8,549.60 €	61,301.60 €	8,724.80 **%**	80

The performance minus direct and operating costs of - € 3.65/ha at Level 1 and 2 is reduced by - € 116.80 due to the expansion of cover crop cultivation across the whole farm. The inclusion of these additional 32 ha of cover crops in carbon farming initiatives increases the performance minus direct and operating costs by € 15.12/ha which equates to an increase of € 1,209.60 compared to Level 2. The removal of the above-ground biomass, which can be done by the subsequent silage maize crop on the entire cover crop cultivation area, increases the performance minus direct and operating costs by another € 8,724.80 compared to Level 1.

Tab. 9-13: Calculation of the performance minus direct and operating costs for the cover crop cultivation before the silage maize for each of the four levels on the farm in the Upper Palatinate.

		LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	
Additional yield		1.5	1.5	1.5	-2.5	t/ha
Increase in subsequent crop yield		9.0 €	9.0 €	9.0 €	-15.0 €	€
Producer price		138	138	138	138	€/t
Cover crop yield					5	t/ha
Producer price					125	€/t
Carbon sequestration				1.26	1.26	t CO_2/ha
CO_2 price				30	30	€/t CO_2
Market performance		**206**	**206**	**244**	**295**	**€/ha**
Seed costs		63	63	63	120	€/ha
N input for additional yield		20	20	20	-34	kg/ha
N supply from cover crop		-60	-60	-60	0	kg/ha
N costs	2.60	-104	-104	-104	-88	€/ha
P input for additional yield		7	7	7	-12	kg/ha
P costs	1.50	11	11	11	-18	€/ha
K input for additional yield		24	24	24	-40	kg/ha
K costs	1.20	29	29	29	-48	€/ha
Fertiliser costs		-64	-64	-64	-154	€/ha
Direct costs		**-1**	**-1**	**-1**	**-34**	**€/ha**
Wages		78	78	78	78	€/ha

Machinery costs		100	100	100	100	€/ha
Diesel costs		54	54	54	54	€/ha
Operating costs		**232**	**232**	**232**	**232**	**€/ha**
Performance minus direct and operating costs		**-25**	**-25**	**12**	**97**	**€/ha**

9.4.3 UPPER PALATINATE - DAIRY FARM

On the farm in the Upper Palatinate, yields are slightly higher than on the Middle Franconia farm, which increases the market performance to € 206/ha. The additional yield also leads to a slight increase in fertiliser costs, resulting in direct costs of - € 1/ha at Levels 1 to 3 and - € 34/ha at Level 4. The operating costs increase again on the Upper Palatinate farm. The reasons behind this are the increase in the amount of fuel consumed, as well as a reduced utilisation of the fleet due to the size of the farm. As such, the performance minus direct and operating costs is lower across all levels when compared to the other two farms. This means that at - € 25/ha, cover crop cultivation at Levels 1 and 2 is no longer profitable there.

Tab. 9-14: Calculation of the cover crop cultivation for the entire crop rotation and total cultivation area on the Upper Palatinate farm.

PERFORMANCE MINUS DIRECT AND OPERATING COSTS	PER ha	PER OPERATION	TOTAL PERFORMANCE MINUS DIRECT AND OPERATING COSTS	DIFFERENCE IN PERFORMANCE MINUS DIRECT AND OPERATING COSTS	COVER CROP AREA
Level 1	**- 25.28 €**	**- 556.07 €**	60,974.63 €	- €	22.0 ha
Level 2	**- 47.63 €**	**- 941.01 €**	60,589.69 €	**- 384.94 €**	27.5 ha
Level 3	**- 28.73 €**	**- 733.11 €**	60,797.59 €	**- 177.04 €**	27.5 ha
Level 4	13.14 €	1,275.98 €	62,806.68 €	1,832.05 €	27.5 ha

The cultivation of 22 ha of cover crop reduced the performance minus direct and operating costs by € 556.07 compared to when the land is left fallow. The performance minus direct and operating costs dropped another € 384.94 when the cover crop was expanded to the maximum of 27.5 ha. One reason for this is the establishment of a cover crop before field peas. The cover crop cannot contain legumes due to the risk of disease developing in the subsequent crop and so can only supply the subsequent crop with 30 kg of nitrogen by preventing leaching. Due to the poor nitrogen supply, the costs of cultivating these additional 5.5 ha cannot be covered. As this land is included in the carbon farming initiatives, the performance minus direct and operating costs increases to -€28.73/ha which corresponds to an additional € 207.90 when compared to Level 2 when considering the entire farm. The cover crop can only be harvested on 22 ha before the silage maize is planted and thus the performance minus direct and operating costs increases by € 1,832.05 when compared to Level 1.

9.5 SUMMARY

Considering the profitability by looking at the performance minus direct and operating costs allows us to compare all performances and costs relevant for a production process, making it a helpful economic decision-making criteria for cover crop cultivation. The yield increase and reduction in the amount of fertiliser used on the subsequent crop are the two factors that have the biggest impact on the profitability of cover crop cultivation. The reduction of fertiliser use is incredibly important at the moment in view of the high fertiliser prices. The costs of removing additional nutrients due to the additional yields heavily depends on the yield and the removal factors of the subsequent crops. The seeds costs can also vary massively depending on the composition of the cover crop mixtures, however they only account for a small proportion of the total cost of a production process. The operating costs have the biggest negative influence on the profitability of cover crop cultivation and can differ significantly from farm to farm depending on the different area structures and work processes used. The use of typical farms for the economic evaluation shows these differences for the different farm types and regions. For most farms, it is economically viable to cultivate cover crops in line with the guidelines laid out in the CAP23 and the German Fertiliser Act (GFA). And the performance minus direct and operating costs of the entire farm can be improved if cover crop cultivation is expanded to as much land as possible. Participation in private-sector carbon farming initiatives also offers a profitable addition. It must be noted that due to the principle of “additionality”, only cover crop cultivation areas outside of the applicable legal guidelines can be included. While the removal of above-ground biomass growth initially brings with it a positive economic performance, it also involves reductions in other performances. The negative influence on the subsequent crop yield reduces performances significantly. The poor nutrient supply also has a negative impact on the performance minus direct and operating costs. Due to various variable influencing factors, cover crop harvesting only makes sense for farms that can make use of the harvested crops themselves. The costs of cover crop fertilisation is not taken into account in the scenarios as this can vary massively depending on the cover crop composition and farm structures. For example, if the cover crop is harvested in spring, organic fertiliser usually needs to be applied in autumn to return the removed values to the soil. This calculation is only intended to show an example of the influencing factors that have to be taken into account when calculating the profitability of cover crops. The flexible factors in the calculation must be adapted to the individual farms and can be optimised by taking into account the results from the individual working groups involved in the CATCHY project.

INFOBOX

IN SHORT

- Evaluation of the profitability based on performance minus direct and operating costs.
- Main benefits of the cover crop: Increase in subsequent crop yields and nutrient supplies, carbon sequestration, value of above-ground biomass.
- Biggest cover crop costs: nutrient requirements for additional yields, seed costs, operating costs.
- The factors that influence the costs and advantages have a wide range and can vary widely depending on the farm and weather conditions.
- Economic evaluation conducted based on data collected from three typical farms for Northern Bavaria.
- The profitability was calculated for four different scenarios: CURRENT state, maximum cover crop cultivation, maximum plus carbon farming, maximum plus carbon farming plus use of growth.
- The performances of the cover crop roughly correspond to the costs on all farms and in all scenarios.
- Some other positive and negative factors could not be considered in the calculation as they are difficult to quantify.

Infobox 9-1.

10. Summary and outlook

Sophia Breische, Carmen Fiedler,

Jan Hendrik Schulz, Matthias Westerschulte

Arable farming is faced with many challenges today. In addition to climate change, new political and social requirements continue to emerge progressively. Cover crop cultivation offers a way to increase the environmental compatibility of integrated crop production without impacting its ultimate purpose - to produce food. The **CATCHY** research project was created to find ways to better exploit the potential of cover crops. During a series of field trials lasting several years, the effects of cultivating cover crops either sown alone or in a mixture were compared with the results from land that had been fallow. The following points in particular were examined: soil structure and quality, microbiome, nutrient and water balances, yield, and profitability. The results of these trials are presented and discussed in this brochure.

Each crop family, species and variety has its own individual spectrum of effects. Therefore, the combination of the various functions in mixtures can help to expand this spectrum of effects and increase the stability of the cover crop. **Compared to cover crop species sown individually, cover crop mixtures offer** agronomic, environmental, and social advantages. However, it is prequesite that mixtures that are adapted to the farm's individual objectives with regards to the crop rotation, the location and the sowing time are utilised. In addition, the effects of cover crops were found to be less effective in intensive crop cultivation systems than in extensive production systems, which are most resemble to natural ecosystems. The results from the project show that cover crops are a useful tool to encourage **formation of soil organic matter** and thus confirm results from comparable publications. The important factor to understand here is the long-term nature of this process. An effective increase in soil organic matter formation can only be achieved through the continuous integration of cover crops in the crop rotation. An important parameter to describe the efficiency here is the C:N ratio of the shoot mass. A low C:N ratio of less than 25 favours microbial processes and increases soil organic matter. In the CATCHY trials, legumes and mixtures containing legumes proved to have the highest potential for formation of soil organic matter.

Cover crop cultivation also helps to **minimise nutrient losses** due to leaching. This is particularly important when it comes to groundwater protection and can be used to support the implementation of the EU Water Framework Directive, particularly in red areas. With reference to nitrogen, the following parameters are decisive when it comes to differentiating between cover crops: the nitrogen binding-potential, the C:N ratio, the time of dying/killing off and the possible incorporation into the soil. Mixtures can help to compensate the weak spots of the individual crops.

Furthermore, cover crops help to improve the formation of water-stable soil aggregates. Again, mixtures show more potential than individual cover crops here. The **improved soil structure** that results from the cultivation of cover crop mixtures offers a range of advantages, including an improvement of the soil water balance and accessibility of the field. Cover crop cultivation can even help to balance out the negative impacts of necessary tilling measures. Cover crops can be an effective and environmentally friendly tool that has a **positive influence on microbial functions in the soil**. The increase in crop diversity in cover crop cultivation results in a greater functionality of the microorganisms in the soil. The greater this functionality is, the more stable the soil ecosystem is when faced with disturbances. This is because almost all soil functions are linked to microbial processes. As each species of crop develops a microbiome that is unique to a specific location, it makes a difference where individual components or mixtures are positioned in a crop rotation. This is proven by the effects on the microbiome in the roots of the subsequent main crop demonstrated in the CATCHY project. For example, the most plant-growth-promoting fungi were found in the roots of maize crops grown after phacelia and the 12-crop mixture, while harmful Fusarium fungi were more frequently found in crops grown after land had been left fallow or planted with mustard. Therefore cover crops can be used as an organic means of control in an even more targeted way in the future, further research into the specific mechanisms of action between cover crops and the main crops in a crop rotation is required. The main principle to remember is that the more diverse the microorganisms that the main crop recruits from the soil, the better it is for crop vitality. Alongside these effects on crop health, the microbial biomass also has an important function as a store and source of carbon and plant nutrients. Cover crops make a significant contribution to **closing nutrient cycles** in arable farming. The nutrient acquisition of a cover crop stand depends on the location, the management, and the crop species / mixture. Individual crop species differ wildly in this respect. The key parameter that come into play here are the speed of the biomass formation, the architecture of the root system and specific mobilisation and immobilisation mechanisms (e.g. exudates and the microbiome described above). In mixtures, the species' individual nutrient acquisition strategies are combined. This means that mixtures can ensure a stable biomass formation and nutrient acquisition in various environments. There are also significant differences between mixtures depending on their composition. This is why it is crucial to choose the right mixture for a specific location based on the nutrient balance and release of the previous main crop and the requirements of the subsequent crop. Nutrient conservation over winter heavily depends on the frost tolerance of the crops. With species that die off early, the nutrient release can begin promptly, but winter-hardy components reduce nutrient losses most efficiently. Combining winter-hardy and frost-sensitive species can be a useful idea as the crop residue left from the frost-sensitive species that die early starts to feed the soil life while crops that grow later store any released nitrogen in the system. The transfer of nutrients to the subsequent crop is, like the winter hardiness and killing off management, heavily dependent on the C:N ratio and working in of the cover crop. The dynamic usually follows this rule:

- Fastest release: Succumb to frost early, low C:N ratio and early incorporation into the soil
- Slowest release: Winter-hardy, high C:N ratio and late working in

Overall, with reference to to the nutrient supply the main crops benefit more, and more quickly, from extensive production systems (like in organic farming) rather than intensive, highly fertilised production systems (like in conventional farming). The important key, is that the positive effects on the nutrient supply are not only visible in the subsequent crop, but in the entire crop rotation. By integrating cover crops into a crop rotation in the long term, it is possible to reduce fertiliser use across the entire cultivation system.

A **complex yield effect** of cover crops on the main crops in the crop rotation occurs based on the described, diverse influencing parameters. With the right management, this effect is certainly positive. However, the short-term yield effects on the subsequent crops are generally rather low and amount to around +0.8 % for silage maize. But ultimately, and more importantly, these yield effects are felt beyond the subsequent crop and extend to the entire crop rotation. For example, when winter wheat was planted after silage maize in long-term trials, yield increases of between 1 % and 4 % were noticed. Furthermore, cover crop mixtures combine the advantages of the individual species and produce the highest potential yield increases. Similar to the positive effects on soil structure and carbon binding, the effects on yield must be considered in the long term.

Cover crop cultivation is an effective agricultural tool that can help to strengthen the **climate resilience** of arable farming. However, to enable it to fulfil the necessary functions, the cover crop stand must be successfully established under increasingly dry conditions after the preceding crop has been harvested. It is vital to work in a way that uses little water and pick the right time to sow the crop. It has been proven that cleverly composed mixtures can offset unforeseeable environmental effects and provide rapid and lasting soil cover.

The results from the project demonstrate that cover crops can **actively control the water balance of the site** where they are planted. Frost-sensitive cover crops can provide the subsequent main crop with more water than fallow land and thus are an advantageous option, particularly as early summer droughts are becoming increasingly frequent. But on the other hand, winter-hardy crops can cause a negative water balance in early spring if they are not actively killed off. This must be avoided in drier locations, but in wetter locations it can help to optimise the spring cultivation of the main crop. The cultivation of cover crops can also help to moderate apparently stressful situations in the subsequent main crops. In the drought years during the project, the cultivation of cover crops resulted in +11 % higher silage maize yields on average.

The wide-ranging effects of cover crop cultivation described above cannot be fully quantified from an economic perspective, even within the framework of a calculation of the direct and operating costs. In terms of revenue, the main points to consider are the potential increase in yields/securing of the yields of the subsequent crop and the savings in fertiliser. Carbon farming can also be an additional revenue factor. The use of cover crop growth can result in a reduction of other performances and only really makes sense if it is going to be used on the farm. In terms of costs, the nutrient removal due to the increase in yield in the subsequent crop and the seed costs are very variable but only take up a small proportion of the overall costs. The highest costs, and thus the parameter with the most optimisation potential, are the operating costs which can vary significantly depending on the farm type, size, cultivation management and machinery used. The integration of cover crops can also be considered **economically viable and profitable** in light of the new legal framework. Especially when considering the many other positive effects that are not financially quantifiable.

The CATCHY project provides important scientific insights into the varied effects of cover crop cultivation in crop production systems based on nine years of research. These insights should ensure a further optimisation of the management of cover crop stands to maximise the beneficial effects and exclude any potentially negative ones. The use of mixtures and the resulting increase in diversity is leading to greater resistance in crop production systems. However, this added value can only be achieved through the continuous integration of cover crops in the cultivation system. With regard to the many challenges that farmers will face with crop production in the coming decades, the use of cover crops is just one measure that they can implement to develop **resilient crop production systems.** The key will be in the overall improvement of soil fertility as a basis for high-yield crop stands. One possible approach may be to actively green the soils as much as possible, keep interventions in the soil to a minimum and increase diversity in the system. In short: the objective should always be to create greener, more biodiverse cover crops.

The basic principles in this brochure can support the development of the necessary, site-specific crop communities. The basis for this are wide crop rotations with appropriately positioned cover crops. In addition, the transitions between the crops should be as smooth as possible and the diversity within the main crops as high as possible. It is also important to develop the use of other measures such as companion cropping, undersowing and mixed crop systems to ensure a systematic selection for farm-specific practical solutions. This also creates enormous further potential for the optimisation of microbiome interactions, soil structure and quality, as well as nutrient and water balances. In this way farmers can secure long-term yields and profitability for their arable farms.

Species directory

ENGLISH NAME	SCIENTIFIC NAME	USE AS A COVER CROP OR A MAIN CROP IN THE CATCHY PROJECT
Legumes		
White lupin	*Lupinus albus L.*	
Yellow lupin	*Lupinus luteus L.*	
Field pea	*Pisum sativum L.*	12-crop mixture
Field bean	*Vicia faba L.*	Main crop (only in crop rotations aimed to increase the content of soil organic matter)
Egyptian clover	*Trifolium alexandrinum L.*	Cover crop sown alone and in a 4-crop mixture
Persian clover	*Trifolium resupinatum L.*	12-crop mixture
Red clover	*Trifolium pratense L.*	
Crimson clover	*Trifolium incarnatum L.*	12-crop mixture
Subterranean clover	*Trifolium subterraneum L.*	
Common vetch	*Vicia sativa L.*	12-crop mixture
Hairy vetch	*Vicia villosa Roth*	
Serradella	*Ornithopus sativus Brot.*	
Grasses		
Italian ryegrass	*Lolium multiflorum italicum*	
Perennial ryegrass	*Lolium perenne L.*	
Red fescue	*Festuca rubra agg. L.*	
Bristle oat	*Avena strigosa Schreb.*	Cover crop sown alone and in a 4-crop mixture
Sudan grass	*Sorghum ×drummondii (Steud.) Millsp. & Chase*	12-crop mixture
Maize	*Zea mays L.*	Main crop
Winter rye	*Secale cereale L.*	
Winter wheat	*Triticum aestivum L.*	Main crop
Winter barley	*Hordeum vulgare L.*	
Chenopodiaceae		
Fodder beet	*Beta vulgaris subsp. vulgaris*	
Polygonaceae		
Tartary buckwheat	*Fagopyrum tataricum (L.) Gaertn.*	
Asteraceae		
Sunflower	*Helianthus annuus L.*	12-crop mixture
Niger	*Guizotia abyssinica (L.f.) Cass.*	12-crop mixture
Brassicaceae		
Abyssinian cabbage	*Brassica carinata*	

White mustard	*Sinapis alba L.*	Cover crop sown alone and in a 4-crop mixture
Winter oilseed rape	*Brassica napus L.*	
Camelina	*Camelina sativa (L.) Crantz*	12-crop mixture
Tillage radish	*Raphanus sativus L.*	12-crop mixture
Oil radish	*Raphanus sativus var. oleiformis*	
Boraginaceae		
Phacelia	*Phacelia tanacetifolia Benth.*	Cover crop sown alone, in a 4-crop mixture and in a 12-crop mixture

References

1. Renius, W., Lütke-Entrup, E. & Lütke Entrup, N. Zwischenfruchtbau zur Futtergewinnung und Gründüngung: Ein Baustein zur Bodenfruchtbarkeit und zum Umweltschutz. 3., überarb. und erw. Aufl. Frankfurt (Main): DLG-Verl (1992).

2. Fründ, H.-C., Hinck, S., Palme, S., Riek, W. & Siewert, C. Bodenfruchtbarkeit: verstehen, erhalten und verbessern. (Erling Verlag, Clenze, 2019).

3. Abdalla, M. et al. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. Global Change Biology 25, 2530-2543 (2019).

4. Lütke Entrup, N. et al. Zwischen- und Zweitfrüchte im Pflanzenbau. (Bundesanstalt für Landwirtschaft und Ernährung, Bonn, 2018).

5. BMEL. Geschichte Der Gemeinsamen Agrarpolitik. Bundesministerium Für Ernährung Und Landwirtschaft. https://www.bmel.de/DE/themen/landwirtschaft/eu-agrarpolitik-und-foerderung/gap/gap-geschichte.html (2014).

6. Clark, A. Managing Cover Crops Profitably. (SARE, College Park, MD, 2007).

7. Kutschera, L., Lichtenegger, E. & Sobotik, M. Wurzelatlas Der Kulturpflanzen Gemäßigter Gebiete Mit Arten Des Feldgemüsebaues. (DLG-Verlag, 2009).

8. Schubert, D., Heigl, L., Mießl, J., Offenberger, K. & Diepolder, M. Wirkung von Zwischenfrüchten. Bayerisches Landwirtschaftliches Wochenblatt 31-33 (2022).

9. Kivelitz, H. Saatzeiten von Zwischenfrüchten optimieren. Landwirtschaftskammer NRW (2017).

10. Hallmann, J., Quadt-Hallmann, A. & Von Tiedemann, A. Phytomedizin: Grundwissen Bachelor. (utb GmbH, Stuttgart, Deutschland, 2009). doi:10.36198/9783838528632.

11. Lütke Entrup, N. Zwischenfrüchte im umweltgerechten Pflanzenbau. (Mann, Gelsenkirchen, 2001).

12. Köppen, D. Bodenfruchtbarkeit im Agroökosystem. 2. (Kovač, Hamburg, 2004).

13. Bodenschutz in der Praxis. (utb GmbH, Stuttgart, Deutschland, 2017). doi:10.36198/9783838548203.

14. Cropp, J.-H. Praxishandbuch Bodenfruchtbarkeit: Humus verstehen | Direktsaat- und Mulchsysteme umsetzen | Klimakrise meistern. (Ulmer, Stuttgart (Hohenheim), 2021).

15. Grundmann, S. Zwischenfrüchte früh säen. Landwirtschaftskammer NRW, Münster Wochenblatt für Landwirtschaft und Landleben, (2019).

16. Zimmermann, D. C. et al. Zwischenfrüchte mit dem Mähdrescher säen. DSV Inovation (2011).

17. Schneider, M. Strohmanagement - Darauf sollten Sie achten! » Landesbetrieb Landwirtschaft Hessen. https://llh.hessen.de/pflanze/marktfruchtbau/wintergetreide/strohmanagement-darauf-sollten-sie-achten/ (2021).

18. Lehrke, U. Frost lässt Zwischenfrüchte absterben. dlv Digitalmagazin App https://www.digitalmagazin.de/marken/landforst/hauptheft/2021-6/pflanzenbau/020_frost-laesst-zwischenfruechte-absterben (2021).

19. Chapagain, T., Lee, E. A. & Raizada, M. N. The Potential of Multi-Species Mixtures to Diversify Cover Crop Benefits. Sustainability 12, 2058 (2020).

20. Couëdel, A., Alletto, L., Tribouillois, H. & Justes, É. Cover crop crucifer-legume mixtures provide effective nitrate cover crop and nitrogen green manure ecosystem services. Agriculture, Ecosystems & Environment 254, 50-59 (2018).

21. Florence, A. M. & McGuire, A. M. Do diverse cover crop mixtures perform better than monocultures? A systematic review. Agronomy Journal 112, 3513-3534 (2020).

22. Cardinale, B. J. et al. Effects of biodiversity on the functioning of trophic groups and ecosystems. Nature 443, 989-992 (2006).

23. Thakur, A. K., Thakur, D. S., Patel, R. K., Pradhan, A. & Kumar, p. effect of different plant geometry and nitrogen levels, inrelation to growth characters, yield and economics on sweet corn (zea mays sachharata l.) at bastar plateau zone.

24. Altieri, M. A. The ecological role of biodiversity in agroecosystems. Agriculture, Ecosystems & Environment 74, 19-31 (1999).

25. Griffin, T. S., Larkin, R. P. & Honeycutt, C. W. Delayed Tillage and Cover Crop Effects in Potato Systems. Am. J. Pot Res 86, 79-87 (2009).

26. Elhakeem, A. et al. Do cover crop mixtures give higher and more stable yields than pure stands? Field Crops Research 270, 108217 (2021).

27. Isbell, F. et al. Benefits of increasing plant diversity in sustainable agroecosystems. Journal of Ecology 105, 871-879 (2017).

28. Poeplau, C. & Don, A. Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis. Agriculture, Ecosystems & Environment 200, 33-41 (2015).

29. Chaplot, V. & Smith, P. Cover crops do not increase soil organic carbon stocks as much as has been claimed: What is the way forward? Global Change Biology 29, 6163-6169 (2023).

30. Hudek, C., Putinica, C., Otten, W. & De Baets, S. Functional root trait-based classification of cover crops to improve soil physical properties. European Journal of Soil Science 73, e13147 (2022).

31. Six, J., Frey, S. D., Thiet, R. K. & Batten, K. M. Bacterial and Fungal Contributions to Carbon Sequestration in Agroecosystems. Soil Science Society of America Journal 70, 555-569 (2006).

32. Bardgett, R. D. et al. Plant species and nitrogen effects on soil biological properties of temperate upland grasslands. Functional Ecology 13, 650-660 (1999).

33. Philippot, L. et al. Loss in microbial diversity affects nitrogen cycling in soil. ISME J 7, 1609-1619 (2013).

34. Mendes, R. et al. Deciphering the Rhizosphere Microbiome for Disease-Suppressive Bacteria. Science 332, 1097-1100 (2011).

35. Santhanam, R. et al. Native root-associated bacteria rescue a plant from a sudden-wilt disease that emerged during continuous cropping. Proc. Natl. Acad. Sci. U.S.A. 112, (2015).

36. Ottow, J. C. G. Mikrobiologie von Böden. (Springer Berlin Heidelberg, Berlin, Heidelberg, 2011). doi:10.1007/978-3-642-00824-5.

37. Koeslin-Findeklee, F. & Horst, W. J. Contribution of Nitrogen Uptake and Retranslocation during Reproductive Growth to the Nitrogen Efficiency of Winter Oilseed-Rape Cultivars (Brassica napus L.) Differing in Leaf Senescence. Agronomy 6, 1 (2016).
38. Ferguson, R. B. et al. Site-Specific Nitrogen Management of Irrigated Maize. Soil Science Society of America Journal 66, 544 (2002).
39. Liu, Z., Chen, Z., Ma, P., Meng, Y. & Zhou, J. Effects of tillage, mulching and N management on yield, water productivity, N uptake and residual soil nitrate in a long-term wheat-summer maize cropping system. Field Crops Research 213, 154-164 (2017).
40. Maidl, F. X., Suckert, J., Und, R. F. & Fischbeck, G. Standorterhebungen zur Stickstoffdynamik nach Anbau von Körnerleguminosen. J Agronomy Crop Science 167, 259-268 (1991).
41. Sieling, K. & Christen, O. Crop rotation effects on yield of oilseed rape, wheat and barley and residual effects on the subsequent wheat. Archives of Agronomy and Soil Science 1-19 (2015) doi:10.1080/03650340.2015.1017569.
42. Thorup-Kristensen, K. Effect of deep and shallow root systems on the dynamics of soil inorganic N during 3-year crop rotations. Plant Soil 288, 233-248 (2006).
43. Lynch, J. P. Root phenotypes for improved nutrient capture: an underexploited opportunity for global agriculture. New Phytologist 223, 548-564 (2019).
44. Dakora, F. D. & Phillips, D. A. Root exudates as mediators of mineral acquisition in low-nutrient environments. Plant and Soil 245, 35-47 (2002).
45. Sun, B. et al. The relative contributions of pH, organic anions, and phosphatase to rhizosphere soil phosphorus mobilization and crop phosphorus uptake in maize/alfalfa polyculture. Plant Soil 447, 117-133 (2020).
46. Rajniak, J. et al. Biosynthesis of redox-active metabolites in response to iron deficiency in plants. Nat Chem Biol 14, 442-450 (2018).
47. Schaaf, G., Erenoglu, B. E. & Von Wirén, N. Physiological and biochemical characterization of metal-phytosiderophore transport in graminaceous species. Soil Science and Plant Nutrition 50, 989-995 (2004).
48. Subbarao, G. V. & Searchinger, T. D. A "more ammonium solution" to mitigate nitrogen pollution and boost crop yields. Proc. Natl. Acad. Sci. U.S.A. 118, e2107576118 (2021).
49. Coskun, D., Britto, D. T., Shi, W. & Kronzucker, H. J. Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. Nature Plants 3, 17074 (2017).
50. Roy, S. et al. Celebrating 20 Years of Genetic Discoveries in Legume Nodulation and Symbiotic Nitrogen Fixation. Plant Cell 32, 15-41 (2020).
51. Heuermann, D. et al. Cover crop mixtures have higher potential for nutrient carry-over than pure stands under changing environments. European Journal of Agronomy 136, 126504 (2022).
52. Komainda, M., Taube, F., Kluß, C. & Herrmann, A. Above- and belowground nitrogen uptake of winter cover crops sown after silage maize as affected by sowing date. European Journal of Agronomy 79, 31-42 (2016).
53. He, M. et al. Divergent variations in concentrations of chemical elements among shrub organs in a temperate desert. Sci Rep 6, 20124 (2016).
54. Eichler-Löbermann, B., Köhne, S., Kowalski, B. & Schnug, E. Effect of Cover cropping on Phosphorus Bioavailability in Comparison to Organic and Inorganic Fertilization. Journal of Plant Nutrition 31, 659-676 (2008).
55. Wendling, M. et al. Influence of root and leaf traits on the uptake of nutrients in cover crops. Plant Soil 409, 419-434 (2016).
56. Gentsch, N. et al. Soil nitrogen and water management by winter-killed cover crops. SOIL 8, 269-281 (2022).
57. Thomas, F. & Archambeaud, M. Zwischenfrüchte in Der Praxis: Eine Anleitung Zur Bewirtschaftung. (Bayer Handelsvertretung, 2018).
58. Böldt, M. et al. Evaluating Different Cover crop Strategies for Closing the Nitrogen Cycle in Cropping Systems-Field Experiments and Modelling. Sustainability 13, 394 (2021).
59. Badawi, A. et al. Verluste Der Oberirdischen Biomasse von Abfrostenden Begrünungspflanzen Durch Ausgasung Vor Der Einarbeitung in Den Boden. (Lehr- und Forschungszentrum für Landwirtschaft Raumberg-GumpensteinRaumberg-Gumpenstein, 2010).
60. Gentsch, N. Cover crops improve soil structure and change OC distribution in aggregate fractions. Zenodo https://doi.org/10.5281/ZENODO.10067563 (2022).
61. Gollner, G., Fohrafellner, J. & Friedel, J. K. Winter-hardy vs. freeze-killed cover crop mixtures before maize in an organic farming system with reduced soil cultivation. Org. Agr. 10, 5-11 (2020).
62. Rüegg, W. T., Richner, W., Stamp, P. & Feil, B. Accumulation of dry matter and nitrogen by minimum-tillage silage maize planted into winter cover crop residues. European Journal of Agronomy 8, 59-69 (1998).
63. Bressler, A. & Blesh, J. Episodic N_2O emissions following tillage of a legume-grass cover crop mixture. Biogeosciences 19, 3169-3184 (2022).
64. Duan, Y.-F. et al. Cover crop Residues Stimulate N2O Emissions During Spring, Without Affecting the Genetic Potential for Nitrite and N2O Reduction. Front. Microbiol. 9, 2629 (2018).
65. Muhammad, I. et al. Regulation of soil CO_2 and N2O emissions by cover crops: A meta-analysis. Soil and Tillage Research 192, 103-112 (2019).
66. Sieling, K. Improved N transfer by growing cover crops - a challenge. Journal of Cultivated Plants 145-160 Seiten (2019) doi:10.5073/JFK.2019.06.01.
67. Wittwer, R. A., Dorn, B., Jossi, W. & Van Der Heijden, M. G. A. Cover crops support ecological intensification of arable cropping systems. Sci Rep 7, 41911 (2017).
68. Langelier, M., Chantigny, M. H., Pageau, D. & Vanasse, A. Nitrogen-15 labelling and tracing techniques reveal cover crops transfer more fertilizer N to the soil reserve than to the subsequent crop. Agriculture, Ecosystems & Environment 313, 107359 (2021).
69. Wendeborn, S. The Chemistry, Biology, and Modulation of Ammonium Nitrification in Soil. Angew Chem Int Ed 59, 2182-2202 (2020).

70. Miller, A. J., Fan, X., Orsel, M., Smith, S. J. & Wells, D. M. Nitrate transport and signalling. Journal of Experimental Botany 58, 2297-2306 (2007).

71. Von Wirén, N. The molecular physiology of ammonium uptake and retrieval. Current Opinion in Plant Biology 3, 254-261 (2000).

72. Subbarao, G. V. et al. Evidence for biological nitrification inhibition in Brachiaria pastures. Proc. Natl. Acad. Sci. U.S.A. 106, 17302-17307 (2009).

73. Jensen, T. Nitrogen fertilizer, forms and methods of application. in Irrigated Crop Production Update Conference (2006).

74. Bending, G. D. & Lincoln, S. D. Inhibition of soil nitrifying bacteria communities and their activities by glucosinolate hydrolysis products. Soil Biology and Biochemistry 32, 1261-1269 (2000).

75. Juliette, L. Y., Hyman, M. R. & Arp, D. J. Mechanism-Based Inactivation of Ammonia Monooxygenase in Nitrosomonas europaea by Allylsulfide. Appl Environ Microbiol 59, 3728-3735 (1993).

76. Dietz, M., Machill, S., Hoffmann, H. C. & Schmidtke, K. Inhibitory effects of Plantago lanceolata L. on soil N mineralization. Plant Soil 368, 445-458 (2013).

77. Robinson, D. -15N as an integrator of the nitrogen cycle. Trends in Ecology & Evolution 16, 153-162 (2001).

78. Viera-Vargas, M. S. et al. Use of different 15N labelling techniques to quantify the contribution of biological N2 fixation to legumes. Soil Biology and Biochemistry 27, 1185-1192 (1995).

79. Blanco-Canqui, H. et al. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. Agronomy Journal 107, 2449-2474 (2015).

80. Chahal, I., Vyn, R. J., Mayers, D. & Van Eerd, L. L. Cumulative impact of cover crops on soil carbon sequestration and profitability in a temperate humid climate. Sci Rep 10, 13381 (2020).

81. Kaye, J. P. & Quemada, M. Using cover crops to mitigate and adapt to climate change. A review. Agron. Sustain. Dev. 37, 4 (2017).

82. Poeplau, C. & Don, A. Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis. Agriculture, Ecosystems & Environment 200, 33-41 (2015).

83. Arora, N. K. Impact of climate change on agriculture production and its sustainable solutions. Environmental Sustainability 2, 95-96 (2019).

84. Praveen, B. & Sharma, P. A review of literature on climate change and its impacts on agriculture productivity. Journal of Public Affairs 19, e1960 (2019).

85. Oldfield, E. E., Bradford, M. A. & Wood, S. A. Global meta-analysis of the relationship between soil organic matter and crop yields. SOIL 5, 15-32 (2019).

86. Adeux, G. et al. Long-term cover cropping in tillage-based systems filters weed community phenology: A seedbank analysis. Field Crops Research 291, 108769 (2023).

87. Fernando, M. & Shrestha, A. The Potential of Cover Crops for Weed Management: A Sole Tool or Component of an Integrated Weed Management System? Plants 12, 752 (2023).

88. Schumacher, M. & Gerhards, R. Facilitation of weed seed predation by living mulch and cover crops. Weed Research 62, 328-339 (2022).

89. Damien, M. et al. Flowering cover crops in winter increase pest control but not trophic link diversity. Agriculture, Ecosystems & Environment 247, 418-425 (2017).

90. Wang, Q., Li, Y., Handoo, Z. & Klassen, W. Influence of cover crops on populations of soil nematodes. Nematropica 79-92 (2007).

91. Javed, M. A. et al. The clubroot pathogen Plasmodiophora brassicae : A profile update. Molecular Plant Pathology 24, 89-106 (2023).

92. Blanco-Canqui, H. & Ruis, S. J. Cover crop impacts on soil physical properties: A review. Soil Science Soc of Amer J 84, 1527-1576 (2020).

93. Koudahe, K., Allen, S. C. & Djaman, K. Critical review of the impact of cover crops on soil properties. International Soil and Water Conservation Research 10, 343-354 (2022).

94. Garba, I. I., Bell, L. W. & Williams, A. Cover crop legacy impacts on soil water and nitrogen dynamics, and on subsequent crop yields in drylands: a meta-analysis. Agron. Sustain. Dev. 42, 34 (2022).

95. Elhakeem, A. et al. Radish-based cover crop mixtures mitigate leaching and increase availability of nitrogen to the cash crop. Field Crops Research 292, 108803 (2023).

96. Finney, D. M., White, C. M. & Kaye, J. P. Biomass Production and Carbon/Nitrogen Ratio Influence Ecosystem Services from Cover Crop Mixtures. Agronomy Journal 108, 39-52 (2016).

97. Wetter und Klima - Deutscher Wetterdienst - Basisfakten zum Klimawandel - Zeitreihen und Trends. https://www.dwd.de/DE/leistungen/zeitreihen/zeitreihen.html?nn=344870.

98. Marschner, P. Chapter 15 - Rhizosphere Biology. in Marschner's Mineral Nutrition of Higher Plants (Third Edition) (ed. Marschner, P.) 369-388 (Academic Press, San Diego, 2012). doi:10.1016/B978-0-12-384905-2.00015-7.

99. Tribouillois, H., Constantin, J. & Justes, E. Analysis and modeling of cover crop emergence: Accuracy of a static model and the dynamic STICS soil-crop model. European Journal of Agronomy 93, 73-81 (2018).

100. Bodner, G., Loiskandl, W. & Kaul, H.-P. Cover crop evapotranspiration under semi-arid conditions using FAO dual crop coefficient method with water stress compensation. Agricultural Water Management 93, 85-98 (2007).

101. Home - agri benchmark. http://www.agribenchmark.org/home.html.

102. Schön J, Gentsch N, Breunig P (2024) Cover crops support the climate change mitigation potential of agroecosystems. PLoS ONE 19(5): e0302139. https://doi.org/10.1371/journal.pone.0302139.

103. Kaul, Sanjana; Choudhary, Malvi; Gupta, Suruchi; Dhar, Manoj K. (2021): Engineering Host Microbiome for Crop Improvement and Sustainable Agriculture. In: Frontiers in Microbiology 12. Online verfügbar unter https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2021.635917.

104. Hamdan, M.F.; Karlson, C.K.S.; Teoh, E.Y.; Lau, S.-E.; Tan, B.C. Genome Editing for Sustainable Crop Improvement and Mitigation of Biotic and Abiotic Stresses. Plants 2022, 11, 2625. https://doi.org/10.3390/plants11192625.

105. Wang, Jun; Zhang, Shaohong; Sainju, Upendra M.; Ghimire, Rajan; Zhao, Fazhu (2021): A meta-analysis on cover crop impact on soil water storage, succeeding crop yield, and water-use efficiency. In: Agricultural Water Management 256, S. 107085. DOI: 10.1016/j.agwat.2021.107085.

106. Schmidt, J. (2023): Über die Zwischenfruchtaussaat per Drohne. Gespräch im Rahmen der Erstellung der CATCHY Dissemination am 16. Februar 2023. Anröchte: Schmidt Solutions.

107. BLE (2018): Zwischen- und Zweitfrüchte im Pflanzenbau. 2. Auflage. Bonn: Bundesanstalt für Landwirtschaft und Ernährung (Hrsg.). ISBN: 978-3-8308-1328-6.

108. Bundesministerium für Ernährung und Landwirtschaft. (n.d.). BMEL - Pressemitteilungen - EU-Agrarreform: Bundeskabinett bringt GAP-Verordnungen auf den Weg. Retrieved July 19, 2024, from https://www.bmel.de/SharedDocs/Pressemitteilungen/DE/2022/145-gap-vo-kabinett.html.

109. Lange, M., Eisenhauer, N., Sierra, C. A., Bessler, H., Engels, C., Griffiths, R. I., Mellado-Vázquez, P. G., Malik, A. A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B. C., Trumbore, S. E., & Gleixner, G. (2015). Plant diversity increases soil microbial activity and soil carbon storage. Nature Communications 2015 6:1, 6(1), 1–8. https://doi.org/10.1038/ncomms7707.

110. Thakur, M. P., Milcu, A., Manning, P., Niklaus, P. A., Roscher, C., Power, S., Reich, P. B., Scheu, S., Tilman, D., Ai, F., Guo, H., Ji, R., Pierce, S., Ramirez, N. G., Richter, A. N., Steinauer, K., Strecker, T., Vogel, A., & Eisenhauer, N. (2015). Plant diversity drives soil microbial biomass carbon in grasslands irrespective of global environmental change factors. Global Change Biology, 21(11), 4076–4085. https://doi.org/10.1111/GCB.13011.

111. Zak, D. R., Holmes, W. E., White, D. C., Peacock, A. D., & Tilman, D. (2003). PLANT DIVERSITY, SOIL MICROBIAL COMMUNITIES, AND ECOSYSTEM FUNCTION: ARE THERE ANY LINKS? Ecology, 84(8), 2042–2050. https://doi.org/10.1890/02-0433.

112. AKEMO, M. C., REGNIER, E. E., & BENNETT, M. A. (2000). Weed Suppression in Spring-Sown Rye (Secale cereale)–Pea (Pisum sativum) Cover Crop Mixes. Weed Technology, 14(3), 545–549. https://doi.org/10.1614/0890-037X(2000)014[0545:WSISSR]2.0.CO;2

113. Altieri, M. A., & Liebman, M. (1986). Insect, weed, and plant disease management in multiple cropping systems. In C. A. Francis (Ed.), Multiple cropping systems (pp. 183–218). New York, NY: Macmillan.

114. Brust, J., & Gerhards, R. (2012). Lopsided oat (Avena strigosa) as a new summer annual cover crop for weed suppression in Central Europe. Julius-Kühn-Archiv, 1(434), 257–264.

115. Buhler, D. D. (2003). Weed biology, cropping systems, and weed management. In A. Shrestha (Ed.), Cropping systems: trends and advances (pp. 245–270). Binghamton, NY: Haworth Press.

116. NRCS. (2017). Module 7 Cover crop management. Soil health & sustainability for field employees. Washington, DC: USDA- NRCS. Retrieved from http://www.cccdwy.net/uploads/2/5/8/1/ 25810027/cover_crop_management.pdf.

117. Griffin, J. N., O'Gorman, E. J., Emmerson, M. C., Jenkins, S. R., Klein, A.-M., Loreau, M., & Symstad, A. 2009. Biodiversity and the stabil- ity of ecosystem functioning. In S. Naeem, D. E. Bunker, A. Hector, M. Loreau, & C. Perrings (Eds.), Biodiversity, ecosystem functioning, and human wellbeing: An ecological and economic perspective (pp. 78–93). New York: Oxford University Press.

118. Bugg, R. L., Sarrantonio, M., Dutcher, J. D., & Phatak, S. C. (1991). Understory cover crops in pecan orchards: Possible management systems. American Journal of Alternative Agriculture, 6(2), 50–62.

Legal notice

PUBLISHER:
BONARES-ZENTRUM
BonaRes is short for “Soil as a sustainable resource for the bioeconomy”. BonaRes is a funding initiative of the German Federal Ministry for Education and Research (BMBF) as part of the German National Research Strategy “Bioeconomy 2030 - Our path to a biobased economy”.

AUTHORS:
Prof. Dr. Barbara Reinhold-Hurek, Dr. Thomas Hurek, Dr. Diana Heuermann, Prof. Dr. Nicolaus von Wirén, Dr. Norman Gentsch, Prof. Dr. Georg Guggenberger, Jonas Schön, Prof. Dr. Peter Breunig, Robin Kümmerer, Sophia Breische, Dr. Ulf Feuerstein, Carmen Fiedler, Jan Hendrik Schulz, Dörte Schweneker, Dr. Matthias Westerschulte, Michał Oskiera

COORDINATION:
Prof. Dr. Hans-Jörg Vogel
Dr. Ute Wollschläger

COMPOSITION AND LAYOUT:
Luise Ohmann (UFZ) Miriam Hantzko (UFZ)

INFO@BONARES.DE

Version 1, Published 12.06.2025