Legume Translated Practice Guide 1

Crop rotations with and without legumes:

a review

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Legumes Translated

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Disclaimer

Translation

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Summary

Legumes are indispensable for the supply of reactive nitrogen into organic farming systems due to their ability to fix atmospheric nitrogen. This reactive nitrogen is used by all arable crops in the organic rotation and forms the foundation of the protein supply for livestock. In conventional farming, legumes offer the potential to diversify crop rotations, especially those dominated by cereals. Legumes 'break' the sequence of cereal crops in these cropping systems. One of the most important consequences of this break-crop effect is the interruption of the life cycle of crop-specific pathogens and the associated savings in pesticides. This review summarises the current state of knowledge on crop rotations with and without legumes. It presents and evaluates the agronomic, environmental and economic effects of the cultivation of large and small legume species as main or catch crops or as components in mixtures. The focus is on relevant publications in scientific journals as well as practice and research reports from 2010 – 2020, carried out in Germany or comparable climatic conditions. From this we derive the necessary research requirements for the subject areas of crop production (conventional and organic), plant protection, economy, ecology and climate protection.

Keywords: Legumes, crop rotation, crop production, crop protection, organic farming, biodiversity, climate protection, economic efficiency, research needs

Introduction

From CASTELLAZZI et al. (2008), we define crop rotations as cyclically recurring sequences of crop species on the same area. Crop rotations are a central component of farming systems. The latter also includes management activities such as tillage, sowing, fertilisation, plant protection and harvesting (VEREIJKEN, 1997). The choice of crop rotation is determined by consumer demand, gross margins, agricultural policy support, market organisation measures and, increasingly, climate change. Simplified, less diverse crop rotations have been a reality in Germany for some time, with the proportion of cereals, especially winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), increasing at the expense of broad-leaved crop species (STEINMANN and DOBERS, 2013; STEIN and STEINMANN, 2018). The four main crops winter wheat, maize, winter barley (*Hordeum vulgare* L.) and winter rape (*Brassica napus* L.) account for almost 70% of Germany`s arable land (DESTATIS, 2019a). The proportion is significantly higher in some districts. These simplified crop rotations, that are widespread today, are also the result of the abandonment of mixed farming, i.e., the result of the spatial and organisational separation of field and livestock farming (KÖPKE, 2013).

There are many agronomic reasons for extending these narrow crop rotations again with broad-leaved (dicotyledonous) crop species such as legumes. Diverse crop rotations maintain, among other things, soil fertility. They exploit phytosanitary effects. Some species have a deep root system, improve soil structure and are considered to be humus-producing (RÜHL et al., 2009). Due to their ability to fix atmospheric nitrogen as a nitrogen input source for the farm cycle and as a basis for domestic protein supply in organic farming, the positive aspects of integrating legumes in crop rotations include breaking the life cycle of crop-specific pathogens, making phosphorus and other nutrients available, and improving soil structure and the water and air balance of the soil (CASS et al., 2014; DAFA, 2012; EVERWAND et al., 2017; FINCKH et al., 2015; CONGREVES et al., 2015; STEFFENS et al., 2005). Decreasing the proportion of cereal cropping results in decreased occurrence of fungal diseases and grass weeds e.g., blackgrass (*Alopecurus myosuroides* Huds.) and brome grasses (*Bromus spp.*). The increasing resistance of pests to insecticides and of grasses to graminicides is also a sensitive issue (DEGNER, 2013).

Leguminous species are particularly suitable for extending cereal-dominated crop rotations to reduce these problems. They are mainly cultivated as spring-sown crops. The straw of grain legumes remains on the field. The targeted use of previous crop effects brings farmers a wide range of benefits (CHRISTEN, 2001; ANDERT et al., 2018; HENNE et al., 2018). There are also winter varieties of pea, faba bean and lupin, but their better adaptation to the climate in central Europe is required.

Linked to nitrogen-fixation, legume seeds are protein-rich. Legumes are mainly used as animal feed in the form of grains or whole plants and are fundamentally indispensable in livestock production.

Recent studies have provided further insights into the phytopathological situation, including the planning of cultivation breaks, nutrient supply and fertilisation, weed control as well as new cultivation methods. These approaches consider mixed cultivation with reduced tillage up to direct sowing after corresponding preceding crops (KÖPKE et al., 2011; WILBOIS et al., 2013; BÖHM et al., 2014; KÖPKE et al., 2016). The results of further experiments on mixed cultivation enabled crop-specific and site-specific recommendations for organic farming (BÖHM et al., 2013). However, the studies also point out that most legumes are selfincompatible ("legume fatigue"), which may require larger intervals between crops of the same or related legume species. Furthermore, some pests occur in both grain and forage legumes (FINCKH et al., 2015).

The closure of existing gaps in knowledge is a prerequisite for the increased integration of legume species in crop rotations. There is already a range of views on the general need for research on legumes from assessments that remain relevant. These include the expert discussion "Cultivation and breeding of legumes in Germany" (WEHLING, 2009), the DAFA Expert Forum on Legumes (DAFA, 2012) and the report by ZERHUSEN-BLECHER and SCHÄFER (2013). Studies focusing on the direct comparison of crop rotations with and without legumes and covering one or more crop rotation cycles have not yet been published. The effects of legume cultivation have mostly only been tested for the direct follow-up crop (PREISSEL et al., 2015; CERNAY et al., 2018).

The aim of the work reported here is to give an overview of the current state of knowledge on the effects of the integration of legumes in crop rotations, to critically evaluate the findings, and to identify existing research needs. This review is based on a study from the Thünen Institute and Julius Kühn Institute from 2018, commissioned by the Federal Ministry of Food and Agriculture (BMEL). In this study, arable, environmental and economic aspects of the cultivation of large- and small-grain legume species were considered, as main or intermediate crop, undersown, or as components in mixtures. The review focuses on studies and research approaches carried out over the last ten years. It concludes with a discussion about research needs in the areas of crop production (conventional and organic), plant protection, biodiversity, climate protection and economics.

Roles of legumes

Despite several support programmes at various political levels (universities, federal states, federal government, EU), the area under grain legumes in Germany and Europe has fallen steadily (Figure 1). Since the introduction of Greening, the cultivation of the grain legumes field bean (*Vicia faba* L.), pea (*Pisum sativum* L.), lupin (*Lupinus spp*.) and soybean (*Glycine max* (L.) MERR.) in Germany has more than doubled from 83,600 ha (2014) to 174,000 ha (2019) (DESTATIS, 2015; DESTATIS, 2019b) (Figure 1).

Nevertheless, the current area under legumes represents less than 1.5% of the total arable land. The share of grain legumes in organic farming, on the other hand, decreased from 31% in 2014 to about 24% in 2018, although the area development of individual legume species was very different (Figure 2). These figures show that the increase in area was particularly pronounced in the conventional sector.

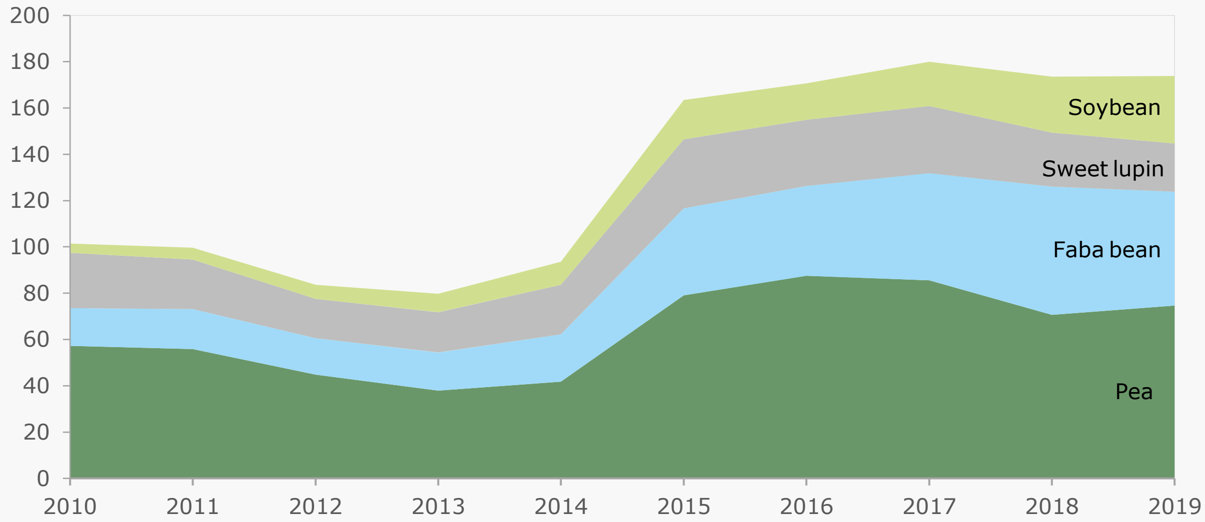

Figure 1. Changes in areas (1,000 ha) under grain legumes for pea, faba bean, lupin and soybean in Germany in the years 2010 - 2019. Own presentation; source: Statistical Yearbook on Food, Agriculture and Forestry (various volumes), ed.: Federal Ministry of Food and Agriculture.

Grain legumes grown in mixture with cereals and other crops were not included. In 2018, 100,900 ha were grown in mixtures in Germany, of which 41,000 ha were organic (SCHAACK et al., 2019). The cultivation of forage legumes has also increased slightly in recent years from 246,000 ha in 2010 to 283,300 ha in 2018. In 2018, 34% of this area, i.e., 96,000 ha, was under organic farming (SCHAACK et al., 2019).

The central problem with grain legumes is that, unlike the more widely grown mainstream crops, their supply chains and markets are not sufficiently developed (MEYNARD et al., 2013). Due to their low market significance, grain legumes are not or only insufficiently farmed, there is a lack of innovation and of adapted nitrogen management, which is necessary for the integration into crop rotations (MAGRINI et al., 2016). However, there are also signs of countering trends. In 2017, for example, a new peak in the area under grain legumes was recorded in Germany. The areas under cultivation of faba bean, soybean and sweet lupin (Figure 3) increased slightly (Figure 1). However, the dependence of legume production on agricultural policy support measures is also clearly visible. After plant protection products were no longer permitted for use on greening areas due to changed support conditions, the areas under pea and lupine immediately declined in the 2018 crop year.

Grain legumes can present challenges in conventional cultivation systems because the nitrogen they fix must be included as an input in the balance as nitrogen due to the 2017 amended German Fertiliser Directive (DÜV, 2017) and the Material Flow Balance Directive (StoffBilV, 2017). In the case of high grain legume yields, high balance surpluses must be reported, which worsens the overall crop rotation nitrogen balance (PAHLMANN et al., 2018).

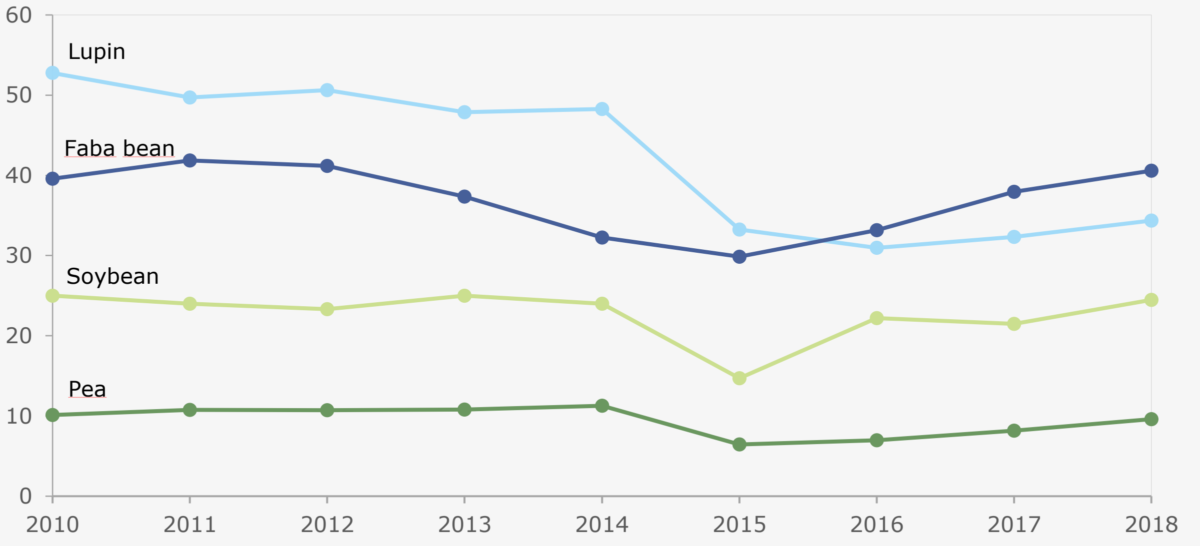

Figure 2. Share (%) of organically grown grain legumes in the total area of each legume species grown in Germany in the period 2010 - 2018. Own presentation; sources: Statistical Yearbook on Food, Agriculture and Forestry (various volumes), ed.: Federal Ministry of Food and Agriculture; AMI Market Study - Structural Data in Organic Agriculture in Germany (various volumes), ed.: Agrarmarkt Informations-Gesellschaft mbH (AMI); AMI Market Balance Sheet Organic Agriculture (various volumes), ed.: Agrarmarkt Informations-Gesellschaft mbH (AMI).

The soybean occupies a special position among the grain legumes. Although there are climatic limits to its cultivation in Europe, soybean, especially non-GM varieties, is said to have considerable potential as an arable crop in Europe (DE VISSER et al., 2014). New varieties have been and are being developed that can also be grown in regions with shorter growing seasons and lower levels of accumulated temperature, quantified as heat sums (ZIMMER et al., 2016).

Legumes are indispensable in organic farming due to their ability to fix atmospheric nitrogen providing reactive nitrogen to the farm system. Especially forage and grain legumes are the basis for the protein supply in livestock production. This usually results in versatile and multi-field crop rotations with legumes in organic farming. Their importance in feeding also leads to a higher economic valuation of legumes compared to in conventional farming. High levels of legumes in crop rotations can also lead to phytopathological problems. In organic farming, therefore, the issue is not "crop rotations with or without legumes", but rather the effect of legumes on non-legume succeeding crops and a sustainable integration of legumes in crop rotations without negative phytopathological side effects.

Figure 3. Testing blue lupin cultivars

Crop production

In the decade 2010 – 2020, a range of agronomic studies with different legume species were carried out and new ones started. In addition to specific studies on selected species in pure seed and mixtures, the demonstration networks for soybean [www.sojafoerderring.de], pea/bean [www. demoneterbo.agrarpraxisforschung.de] and lupin [www. lupinen-netzwerk.de] are particularly noteworthy. Research and development projects such as the BLE-funded project RELEVANT (Regulatory ecosystem services in crop rotation with faba bean and pea: quantification, evaluation and implementation; cf. chapter on biodiversity) were linked to these demonstration networks (SCHULZ et al., 2019).

Important issues of grain legume cultivation in organic farming have been taken up and addressed (KÖPKE et al., 2011; WILBOIS et al., 2013; BÖHM et al., 2014; KÖPKE et al., 2016) in the framework for joint projects. Zero-tillage methods for sowing faba bean in an oat straw mulch have been established. This performs well where there is low pressure from perennial weed species (KÖPKE et al., 2011). Studies on reduced tillage in forage inter-cropping systems using winter pea (Figure 4) also showed no differences in weed suppression compared to ploughing. The investigated mixtures showed a significantly lower aphid infestation compared to pure stands of winter pea (GRONLE et al., 2014). This could be attributed to low N content of the pea kernels grown in the mixture. In this context, the use of a normal-leaved variety produced higher grain yields than a semi-leafless variety in pure stand and in the mixture (GRONLE et al., 2015).

Studies on grain and forage legumes showed that sulphur fertilisation of grain legumes rarely has a positive effect on yield and quality due to their relatively low sulphur requirement (SCHMIDTKE and LUX, 2015; GRUBER and WEGNER, 2017). Forage legumes clearly respond positively to sulphur fertilisation because the N-fixing capacity and thus the pre-crop value is increased (FISCHINGER et al., 2011; BECKER et al., 2013; BÖHM, 2016).

For the agronomic assessment of the effect of including legumes in crop rotations, it is useful to distinguish between the nitrogen effect and the break-crop effect (JENSEN, 2006). Both effects together account for the pre-crop value of grain legumes. In contrast to the legume-specific nitrogen effect, the break-crop effect is not linked particularly to legumes but is the result of the interruption of monotonous crop rotations. The break-crop effect could therefore also be described as a diversification effect which can also be achieved with other broad-leaf crops such as oilseed rape. One of the most important consequences of the break-crop effect is the breaking of the life cycle of crop-specific pathogens, which enables pesticide savings (MUNIER-JOLAIN and Collard, 2006). The benefits of introducing grain legumes are particularly great in farming systems with a high proportion of cereals. By contrast, in regions with already diverse crop rotations (e.g., in Switzerland), it is often not possible to achieve a break-crop effect at all by including grain legumes in the crop rotation (NEMECEK et al., 2008). There are also indications that the direct preceding crop has a greater influence on the yield level of the subsequent crop than the entire preceding rotation, i.e., that the preceding crop effect is greater than the crop rotation effect (GREEF et al., 2004).

Two recent meta-studies confirm the positive effect of grain legumes on the yields of the subsequent crops (PREISSEL et al., 2015; CERNAY et al., 2018). The analysis of the global data from international peer-reviewed journals covering a total of 15 countries showed that the yield of grain after grain legumes was on average 29% higher than the yield of grain after grain (CERNAY et al., 2018). However, the positive effect of grain legumes decreased with increasing nitrogen fertilisation to the subsequent cereal crop and was even negligible above 150 kg N ha^{-1}. This critical value of 150 kg N ha^{-1} is often exceeded in conventional European cereal cultivation systems. PREISSEL et al. (2015) also showed increased cereal yields after grain legumes of 0.5 to 1.6 t ha^{-1}, whereby the additional yields from a legume preceding crop were also highest with low nitrogen fertilisation to subsequent crops. However, this additional yield was only slightly higher than when another leafy preceding crop such as rape or sunflower was chosen. In principle, the introduction of grain legumes in crop rotations could therefore achieve high cereal yields even with significantly reduced nitrogen application.

BRAUN et al. (2014) compared a range of crop rotations with and without legumes and catch crops (an arable farm, a livestock farm with biogas plant and a farm optimised for greenhouse gas emissions (GHG)). In the extended crop rotation on the GHG-optimised farm, the winter barley grown clearly benefited from the preceding faba bean (RÖPER et al. 2017). It should be noted, however, that the faba bean residues increased autumn N_{min} values. In a long-term experiment (1988-2001) at the Christian-Albrechts-University

Figure 4. Mixed cultivation of white winter pea and winter triticale.

of Kiel, a total of 15 different crop rotations were compared in northern Germany, which included winter oilseed rape, winter wheat, winter barley, pea and oat (*Avena sativa* L.) (SIELING and CHRISTEN, 2015). To allow crop rotation comparison, winter wheat was grown twice to quantify the effect of preceding crops or crop rotations on growth, yield and yield components. The highest wheat yields were achieved in the first year after pea and winter rape. Second cereal yields were unaffected by the legume.

SCHNEIDER et al. (2012) conducted trials on organic crop rotations with the aim of comparing crop rotations with different legume species and their use in terms of yield performance (including crop rotation yield and economic valuation) and the qualities of the non-legume crops grown after legumes. Crop rotations based on grass-clover cut for livestock achieved the highest productivity based on cereal units. When comparing crop rotations with grain legumes without on-farm use and crop rotations with clover-grass that is mulched, the latter proved to be superior in terms of the yield of market crops (SCHNEIDER et al., 2012). However, the overall productivity of the two systems did not differ.

N_2O emissions and maize grain yield were measured over three growing seasons in a 50-year crop rotation experiment in Canada (DRURY et al., 2014). In rotation with alfalfa, the maize grain yield was on average almost twice as high as in the maize-only sequences. Equal amounts of N, P and K were applied as a starter fertiliser and incorporated into the upper 10 cm soil layer for both variants. Using yield and weather data (1982 - 2012) from another Canadian long-term trial, GAUDIN et al. (2015) investigated the yield stability of maize grown in monoculture and grown in crop rotations that included soybean and lucerne as main crops and clover undersown in cereals. Although the magnitude of crop rotation benefits varied according to crop, weather conditions and tillage practices, the yield stability of maize and soybean increased significantly in the more diverse crop rotations. The benefits of diversified crop rotation were particularly evident in unfavourable weather conditions (cool-humid, dry-hot). Overall, the study showed that more diverse crop rotations contribute to increased yield stability of cereals.

Another long-term three-site crop rotation experiment was started in Denmark in 1997 with one conventional and two organic crop rotations with and without the use of anaerobically treated manure, green manure (alfalfa or grass mixture with red and white clover), and catch crops (including pea) (DE NOTARIS et al., 2018). For the first three crop rotation cycles (1997 - 2008), the crop rotation of spring barley - clover grass (mulched) - potato - wheat with integrated green manure tended to show higher dry matter yields in the third cycle in all locations (OLESEN et al., 2011; SHAH et al., 2017). The organic rotations produced between 21 to 64% of the yield of the conventional rotation in the third cycle. This yield difference could be most significantly reduced by using farm manures. In addition, year-round green manure (clover grass, mulched) and leguminous-based catch crop mixtures could improve yield performance. However, the use of year-round green manure reduces cropping for food so that the overall productivity of the farming system is not increased.

While the effect of legumes on the yield of the subsequent crop is relatively easy to measure, other effects, such as pest and pathogen pressure, changes in soil structure or root growth are difficult to quantify. A long-term experiment confirmed that grain legumes are less supportive of soil organic matter gains compared to grass clover, while with regard to organic matter content and quality, no differences were found between the form of clover grass use (cut with removal followed by return via organic manure vs. mulching) (URBATZKA and BECK, 2015).

CONGREVES et al. (2015) evaluated four long-term crop rotations with lucerne, soybean and clover as undersown crops in Ontario (Canada) with regard to the effects on soil health. The aggregate stability and organic matter content were enhanced by lucerne. The effect of individual crops within a crop rotation seems to be more decisive for soil health than the extent of the diversity (CONGREVES et al., 2015).

In addition, there are effects related to the availability of nutrients other than nitrogen. For example, legume species such as white lupin, chickpea or faba bean can mobilise phosphorus that is difficult to obtain via root excretion of organic acids (HOCKING, 2001; STEFFENS et al., 2005) and improve the supply of plant-available phosphorus to succeeding crops (NURUZZAMAN et al., 2005). Legume species with taproots can also improve soil structure and enrich the soil with organic carbon (ROCHESTER et al., 2001; ASLAM et al., 2003), thus enabling the succeeding crop to root deeper (KAHNT, 2008).

The EU project Legume Root Impact dealt with the time course of decomposition of root systems of forage mixtures (red and white clover) in the soil. The faster decomposing leaf mass plays a much greater role in the short-term carbon and nitrogen turnover in the soil than the root mass (CORDIS, 2014).

In addition to these studies of crop rotation effects, research results also consider the optimal placing of forage and grain legumes in crop rotations. These include results about the effect of preceding and intercrop positions on different soil types and information on the organic fertilisation of different legume species (KOLBE, 2009; SCHLATHÖLTER, 2015; SCHLATHÖLTER and PETERSEN, 2015; BÖTTCHER and SCHMIDT, 2016; PAHLMANN and KAGE, 2018; STUTE and SCHÄFER, 2018). The cultivation of over-wintering legume catch crops or catch crop mixtures can protect nutrients from being leached out and suppress weeds. The use of frost-sensitive catch crops is advantageous here. If spring growth is allowed, possible restrictions in the water supply following the catch crop must be considered (BÖTTCHER and SCHMIDT, 2016). Complex crop rotations can have positive effects on nitrogen efficiency and balance, but they make it more difficult to apply nitrogen fertilisation in line with the needs of individual crops.

As a disadvantage of crop rotations with grain legumes, NEMECEK et al. (2008) cite the increased nitrate leaching potential, which is related, among other things, to the symbiotic nitrogen fixation or the difficult-to-calculate mineralisation of organically bound nitrogen. According to the authors, this problem can be reduced by using catch crops, winter grain legumes or mixed cultivation.

A Danish study of two organic and one conventional crop rotations over several years with and without the use of anaerobically treated manure, green manure [alfalfa or grass mixture with red clover (*Trifolium pratense* L.) and white clover (*Trifolium repens* L.)] and catch crops (including pea) also shows results on nitrate leaching (DE NOTARIS et al., 2018). In both conventional and organic systems, legume and non-legume catch crops were able to reduce nitrogen leaching by an average of 60% in the fourth cycle of the crop rotation experiment. In organic farming with grain legumes, the use of catch crops also increased nitrogen supply by an average of 20 kg N ha^{-1} annually. The nitrogen leaching risk was higher in organic farming with green manure (2-yearly mulched clover grass) than in the other farming systems.

In addition to the different effects of legumes on succeeding crops, the effects of non-legumes on legumes in mixtures or as preceding crops have also been examined (CORDIS, 2015). In the EU PROLEGSO project, the legumes red clover, white clover and trefoil (Lotus spp.) benefited in terms of yield from non-legumes such as ryegrass (Lolium perenne L.), tall ryegrass (*Anthoxanthum odoratum* L.), ribwort (*Plantago lanceolata* L.) and yarrow (*Achillea millefolium* L.), which grow slowly and absorb little phosphorus and potassium. Such non-leguminous plants could improve the soil for legumes by promoting symbiotic organisms (mycorrhiza fungi, rhizobia).

However, there are limits to the integration of legumes in crop rotations, as some species are sensitive to over-frequent cultivation due to self-incompatibility. SCHMIDT et al. (2014), for example, were able to show in studies on organically managed farms that the grain yield of white-flowering pea decreases with increasing frequency of cultivation. Therefore, they derived a cultivation interval of at least 9–10 years for white flowering pea instead of the previously recommended 5–6 years. The reason for this is the soil-borne pests belonging to the so-called *Ascochyta* complex of the pea (foot and focal spot diseases), such as *Mycoshaerella pinoides* and *Phoma medicaginis* (KRAFT and Pfleger, 2001; Finckh et al., 2015), some of which have a survival period of more than ten years in the soil. According to BRETAG et al. (2001), they can cause yield losses of up to 75%. In addition, some of these and other pests can occur on both grain and forage legumes (FINCKH et al., 2015). Table 1 shows the currently recommended cultivation distances for the most commonly cultivated legume species.

Table 1. Recommended cultivation breaks for different types of legumes. Sources: DemoNetPeaBean (2020), KTBL (2013).

Forage legumes		**Grain legumes**	
Species	Years	Species	Years
Seradella	1 - 2	Soybean	1 - 3
White clover	1 - 3	Faba bean, lupin, vetch, lentil	5 - 7
Alexandrine clover, Persian clover	3 - 4	Austrian winter pea	5 - 9
Red clover, sweet clover, lucerne, sainfoin, yellow clover, incarnate clover	4 - 7	Pea	6 - 10

Further findings on crop rotation effects of legumes can be expected in the future from the new EU projects launched under the Horizon 2020 programme. These are concerned with creating the conditions for successful cultivation systems using clover (*Trifolium spp.*), faba bean, lentil (*Lens culinaris* MEDIK.), lupin, soybean, chickpea (*Cicer arietinum* L.), common bean (*Phaseolus spp.*), grain pea, alfalfa (*Medicago sativa* L.) and cowpea [*Vigna unguiculata* (L.) WALP.]. A further focus is on identifying the benefits of species mixtures including legumes such as grain pea, clover, fenugreek (*Trigonella foenum-graecum* L.) and vetch (*Vicia spp.*) in developing diversified and resilient farming systems that are less dependent on external inputs (EU ReMIX project). The Thematic Network (H2020) Legumes Translated, launched in November 2018, is also promising. The network aims to gather existing knowledge on grain legume cultivation, bring together agricultural innovators and scientists and jointly develop practical recommendations for the cultivation of grain legumes (MURPHY-BOKERN et al., 2019; CORDIS, 2020).

Crop protection

Successful legume production depends on the availability of resistant cultivars and sufficient availability of plant protection products and procedures, combined with monitoring of target organisms and field hygiene (Stoddard et al., 2010). While highly efficient plant protection products are available for the major arable crops, the chemical toolbox for legumes is rather limited. Little research on the incidences of pests in central Europe has been done. Evidence relevant to crop protection is often limited to international studies (SILLERO et al., 2010). The occurrence of typical legume pests is influenced by the frequency of legume cultivation in a region, but also by legumes growing naturally in grassland areas and along field margins. Arable crops other than legumes are generally not affected by pests of specific to legume species.

Fungal diseases

The review by SILLERO et al. (2010) on the occurrence of harmful pathogens and the possibilities of control concludes that the crop rotation and annual weather conditions in conjunction with the used tillage methods are often largely responsible for the occurrence of infection in the cultivation of large-grained legumes. In crop rotations with sugar beet (*Beta vulgaris* ssp. *vulgaris*) or rapeseed, there is a risk that soil-borne pests such as *Rhizoctonia* spp. and *Sclerotinia* spp. increase in the soil (NOACK, 2016). Due to their broad host spectrum, these diseases can become a cross-crop problem for the entire crop rotation. It is therefore important to observe appropriate pauses in cultivation (cf. Table 1).

The spread or transmission of crop rotation diseases is currently considered to be less significant for soybean. *Diaporthe* spp. and *Phomopsis* spp. are two important harmful fungi known from other growing regions of the world (XUE et al., 2007) which can cause considerable damage to soybean stems, pods and seeds in large-scale cultivation. The emergence and establishment of soybean stands can currently be improved by using seed treatments with the active ingredients fludioxonil, metalaxyl, difenoconazole and trifloxystrobin as well as the biological preparation *Clonostachys rosea* (XUE et al., 2007). However, some of these active substances will be withdrawn in the future due to a re-evaluation by the EU Commission under Regulation 1107/2009/EU. According to SHUXIAN and CHEN (2012) sources of resistance are available for breeding.

Attempts to combat the above-mentioned diseases with biological means such as resistance inducers and plant extracts have not been successful (STODDARD et al., 2010). In contrast, there are promising approaches that anthracnosis (Figure. 5) caused by *Colletotrichum* spp., can be biologically controlled by *Clonostachys* spp., *Bacillus subtilis* or *Pseudomonas putida* (TINIVELLA et al., 2009).

Pests

According to studies by HEIN (2006), the loss through pests is higher than that through harmful fungi. In addition to damage caused by direct infestation of the crop plant, the function of the pests as virus vectors (e.g., PNYDV transmitted by *Acyrthosiphon pisum*) must also be taken into account (MÄNNEL et al., 2018).

Figure 5. Anthracnose in white lupin

Causes for increasing economic damage are the lack of availability of both effective insecticides and lack of tolerant or resistant varieties. According to current knowledge, the increase in insecticide resistance (e.g., of aphids to pyrethroids) will further reduce the possibilities for targeted control.

The pea moth *Cydia nigricana* is a specific pest of pea. Increases in the proportion of pea crops in a region promote the occurrence of this pest (HUUSELA-VEISTOLA & Jauhiainen, 2006). This also applies to other legume pests: increases in production increases the risk for individual crops. It should be noted that the black bean aphid (*Aphis fabae*) attacks not only faba bean but also non-leguminous crops such as beet and various wild plants, but not pea.

Fine-seeded (forage) legumes are also infested by specific insect pests such as various seed beetles (*Bruchidae*), leaf beetles of the genus *Sitona* and the weevils of genus *Hypera.* Polyphagous aphid species such as *Myzus persicae* may be relevant as virus carriers in different crops. Wireworms (larvae of *Elateridae*) can infest old stands of fine-seeded legumes (clover, alfalfa).

Some studies have also examined the effects of intercropping, i.e. the cultivation of mixtures of grain legumes and other crops, usually cereals. In many cases, a reduction in aphid infestation (*Myzus persicae*) was found in the intercropping variants (SEIDENGLANZ et al., 2011; BEDOUSSAC, 2009; GRONLE et al., 2014), while no differences were found in pea moth (*Cydia nigricana)* (GRONLE et al., 2014).

Weeds

The assessment of existing research results shows that the control of weeds and grass weeds has a significant influence on the establishment of legumes in a standard crop rotation. Particularly with respect to grass weeds, grain legumes have only a low weed suppression capacity due to their slow growth (BÖHM, 2014). The availability of suitable control measures is very limited. This is regarded as a limiting factor for growing legumes on some farms. Studies by public advisory services show that mechanical methods such as hoeing on the whole cropped are very effective, especially under dry soil conditions (Figure 6.)

Figure 6. Possibilities of mechanical weed control in legumes. On the left: Use of a rolling harrow in Blue Lupines; right: Use of a chopping harrow in forage peas.

Some of the measures can be taken before the crop emerges, taking into account the seed placement depth. This closes gaps in the effectiveness of usable herbicides. Hoeing equipment in combination with optical methods and digital recording and control units can achieve higher efficiencies (e.g., Gerhards et al., 1998; Heinold et al., 2018; Heuser et al., 2018).

Biodiversity

The use of grain legumes such as soybean or faba bean and forage legumes such as lucerne and various clover species in arable crop rotations has potentially diverse impacts on wild arable flora, insects and vertebrates and thus on biodiversity in agricultural landscapes (CASS et al., 2014; EVERWAND et al., 2017). In general, each additional crop in the crop rotation represents an increase in the species spectrum and thus contributes to genetic diversity within agrobiodiversity. Furthermore, legumes have specific properties that can promote components of biodiversity in their environment, both above and below ground. These include the ability to biologically fix N, a close C/N ratio of plant biomass (AHER et al., 2017), extrafloral nectaries (FREE, 1962) and a stand architecture that differs from that of cereals (ABBO et al., 2009). Due to mass flowering, legume crops that flower can support generalist pollinator species in agricultural landscapes (BEYER et al., 2020), as other mass flowering crops such as oilseed rape do (WESTPHAL et al., 2003). However, leguminous crops are often more versatile in use than other crops. In addition to their use as a main crop, legumes can also function as green manure, catch crop and as a partner in mixed cultivation, especially with cereal crops (pea/barley, field bean/ wheat, etc.). In this way they can contribute to both spatial and temporal diversification of crop rotations, which can result in differentiated impacts on biodiversity (TAMBURINI et al., 2020). In the following, we discuss the effects of legume cultivation on pollinating insects, predatory and herbivorous arthropods and earthworms.

Despite the well-known importance of pollination as an ecosystem service (GALLAI et al., 2009), there is growing evidence of the decline in pollinators around the world (POTTS et al., 2010). This decline is linked, among other things, to the loss of habitats and food resources (GOULSON et al., 2015). Flowering legumes (Figure 7), which provide a food source for nectar-gathering and pollinating insects in agricultural landscapes, can have a beneficial effect here (WOODCOCK et al., 2014). Forage legumes such as clover, sainfoin (*Onobrychis spp.*), vetches and lucerne provide pollinators with a rich supply of flowers. Grain legumes, on the other hand, have a lower flowering supply, but they can function as honey bee feeding crops when incorporated into crop rotations (MINISTRY OF RURAL AREAS AND CONSUMER PROTECTION, 2019). Crops that feed honey bees are particularly rich in nectar and pollen and are therefore preferred by bees for the production of honey. To close gaps in the bee ranges, in addition to forage and grain legumes as main crops, the most suitable crops are white and incarnate clover (*Trifolium incarnatum* L.) undersown in cereals. These two species flower when the rape and other mass flowering crops (e.g., fruit) have passed (MINISTRY OF RURAL AREAS AND CONSUMER PROTECTION, 2019). BEYER et al (2020) showed that bumblebees with long tongues are more common in landscapes with faba bean than in comparable landscapes without faba bean. This effect remained even after the faba bean had flowered. So far, breeding of grain legumes has drawn self-pollination and focused on yield, rather than on pollen and nectar availability and an adapted flower shape (PALMER et al., 2009). This is despite the fact that studies have shown that pollination by insects has a positive effect on yield, even with largely self-pollinating species such as soybean or pea (CHIARI et al., 2005, MONASTEROLO et al., 2015, NAEEM et al., 2018). Consequently, much of the potential of grain legumes as forage for pollinators that close gaps in forage availability and thus promoting ecosystem services by pollinators remain untapped. Increasing open pollination would have to be weighed against the possible economic advantages of self-pollination. In addition to floral nectar, many legumes provide extra-floral nectar that can be used not only by pollinators but also by other beneficial species such as parasitoid wasps (GÉNEAU et al., 2012).

It is generally believed that the whole trophic chain benefits from an improved supply of nitrogen and protein from legumes. Herbivorous and omnivorous arthropods benefit directly from the nitrogen- and protein-rich residues of legumes (CASS et al., 2014). Whether this can lead to a one-sided promotion of pests or to the control of these pests by their natural enemies is not clear. Only a few individual studies are currently available. The species richness of ground beetles (Carabidae) tended to be higher in soybean fields than in other arable crops such as maize, oat, sunflower (*Helianthus annuus* L.) and wheat (ELLSBURY et al., 1998; LARSEN et al., 2003; O'ROURKE et al., 2008; DE LA FUENTE et al.; 2014; MOLINA et al., 2014). YOUNG & Edwards (1990) reported in a review article on a significantly increased species richness of spiders (*Araneae*) in soybean compared to many other crops such as rice (Oryza *sativa L.)*, sorghum millet [Sorghum *bicolor (L.*) MOENCH], maize and sugarcane (Saccharum *officinarum L.)*. Only other legumes (especially perennials) showed a higher species richness and activity than soybean. This relationship was further investigated in a scientific study comparing alfalfa, as an annual or perennial crop, with the annual soybean. From the second year onwards, alfalfa always showed higher activity and species richness in spiders than in soybean (CULIN & Yeargan, 1983a and 1983b). In a report on the influence of legumes on biodiversity, CASS et al (2014) listed numerous sources that showed the positive influence of legume cultivation (especially soybean, lucerne, lupin and clover) on the activity of predatory arthropods and parasitoid wasps (CURRY, 1986; OSLER et al., 2000; HOOKS & Johnson, 2001; Midega et al., 2009). The beneficial effect of soybean on predatory arthropods has been demonstrated up to the subsequent crop (BRUST et al., 1986). In addition to such previous crop effects, neighbourhood effects can also be beneficial. SCHULZ-KESTING et al. (2021) showed that the density of aphid mummies was higher in wheat fields bordering on faba bean fields than in fields adjacent to other wheat fields. The density of aphid mummies indicates the parasitisation rate of aphids. At the same time, the density of herbivorous insects was not increased by the proximity of faba bean crops.

Figure 7. Flowering diversity of grain legumes. Above: faba bean, soybean, coloured flowering winter pea, white flowering spring pea; below: Blue lupin, yellow lupin, seed vetch and flat pea (from left to right).

Earthworms (*Lumbricidae*) are used as indicators of biodiversity and soil fertility because of their essential role in agroecosystems (BARTZ et al., 2013). Legumes influence both species richness and earthworm activity. The cultivation of forage legumes such as clover (Figure 8) had a positive effect on the activity and species richness of earthworms both in a mixture in grassland and in catch crop cultivation (SCHMIDT et al., 2003; JORDAN et al., 2004; BIRKHOFER et al., 2011). In the case of grain legumes, however, the literature does not provide a clear picture. SMITH et al. (2005) reported higher earthworm activities in soybean compared to other arable crops. ASHWORTH et al. (2017) in turn presented contradictory results. In a field experiment, soybean showed a higher activity density than maize. In a second field experiment, however, maize promoted the earthworm population more strongly than soybean.

From the existing limited knowledge it can be concluded that the integration of legumes in crop rotations can potentially enhance biodiversity and the ecosystem services associated with it. However, a positive impact also depends on the type and intensity of crop management in the crop rotations. There is very little research on legume rotations in terms of biodiversity and ecosystem services (Ditzler et al., 2021). As a result, there is a lack of knowledge about the influence of legumes under specific site conditions (e.g., rainfall, air temperature, soil water content, soil type) in combination with crop management measures on different groups of organisms. To date, there is insufficient reliable knowledge for legume species in crop rotations to be able to make reliable statements about their influence on biodiversity and ecosystem services in central European arable farming systems.

Figure 8. White clover (*Trifolium repens* L.) for forage use

Climate protection

The greenhouse gas balance of arable farming is most strongly affected by the input of organic carbon and organic nitrogen as well as synthetic nitrogen. There are four main pathways leading to net greenhouse gas emissions:

1. Naturally occurring processes of the nitrogen cycle, i.e., nitrification, denitrification and other processes (BUTTERBACH-BAHL et al., 2013) produce nitrous oxide (N_2O) from mineral nitrogen as an intermediate and/or end product, which is then released. These processes take place either directly in the field (direct emissions) or after nitrate leaching or ammonia deposition elsewhere (indirect emissions).
2. Soil carbon is mineralised in unsaturated soils. The quantity and quality of carbon input to the soil (through organic fertilisation and above and below ground crop residues) and climatic and soil characteristics (which influence the rate of mineralisation) together determine whether there is a net loss or gain of soil carbon.
3. Greenhouse gas emissions result from energy use and nitrous oxide emissions during the production of synthetic fertilisers.
4. The energy use by agricultural machinery causes CO_2 emissions.

According to IPCC regulations (IPCC, 2006), only point 1 is reported under source category "agriculture" in national GHG inventories. Point 2 is reported under category "land use, land use change and forestry" (LULUCF), while points 3 and 4 are reported under categories "industry" and "energy". Nevertheless, mitigation of emissions is necessary in all these categories (BMU, 2016). The German Climate Protection Act (BUNDESGESETZBLATT, 2021) sets ambitious targets for greenhouse gas savings in agriculture (including energy consumption). It defines binding emission budgets that start at 70 million t CO_2-eq. in 2020 and are reduced to 56 million t CO_2-eq. by 2030. Beyond that, it mandates an 88% reduction by 2040 compared to 1990.

Increasing the legume share in crop rotations is generally recognised as a climate protection measure (cf. NEWELL PRICE et al., 2011). The effect results from the substitution of synthetic nitrogen fertilisers by biological nitrogen fixation (WANG et al., 2018). In addition, the field traffic for application of fertiliser is avoided, thus saving energy. Since biological nitrogen fixation is a foundation of organic farming, the aim of managing more land organically (FEDERAL GOVERNMENT, 2017) is also a contribution to climate protection.

It is currently assumed that the process of biological nitrogen fixation and the supply of that reactive nitrogen to the host legume plant do not produce nitrous oxide (IPCC, 2006; ZHONG et al., 2009). REES et al. (2013) quantify annual mitigation potentials between 0.5 and 1 t CO_2 equivalents per hectare for Great Britain through increased use of nitrogen fixation of clover and introduction of additional species (including legumes) in crop rotations. However, the mitigation potential at the level of the cropping system is strongly dependent on the type of legume and climate. On the one hand, these factors influence the performance of nitrogen fixation (LIU et al., 2011) and on the other hand, nitrous oxide emissions depend strongly on soil moisture and temperature (BUTTERBACH-BAHL et al., 2013) at times of high nitrogen availability in crop rotations (e.g., after harvest or incorporation of legumes). Moreover, the amount of nitrous oxide from nitrogen in crop residues is still unclear. The IPCC (2006) made the rough assumption that the same emission factor (1% of added N) applies to nitrogen from crop residues as it does to fertiliser nitrogen, i.e., that 1% of the nitrogen in residues or applied as fertiliser is emitted as nitrous oxide regardless of the type of nitrogen (mineral, organic from farm fertilisers or plant residues). In future, it is to be assumed that (outside dry regions) direct nitrous oxide emissions from the nitrogen in crop residues are 37.5% of emissions after application of the same amount of nitrogen in synthetic fertilisers (IPCC, 2019). The basis for this is a purely empirical meta-analysis without consideration of process interrelationships (IPCC, 2019, Annex 11 A.2) and no targeted studies. There is therefore still a considerable need for research in this area.

A meta-analysis of German measurement studies did not support the distinction between synthetic and organic reactive nitrogen inputs. Instead, emission factors stratified by environmental regions and between mineral and organic soils were derived (Mathivanan et al., 2021). The resulting average emission factor for crop residues in Germany is 0.6% and thus very close to the value proposed by IPCC (2019). However, the emission factor for synthetic fertiliser nitrogen inputs in Germany is of the same magnitude, i.e., lower than proposed by IPCC (2019).

Overall, however, it is not yet clear whether increased legume cultivation compared to the status quo could lead to increased nitrous oxide emissions in the field due to increased input of nitrogen together with easily degradable organic matter when legume biomass is incorporated. In their meta-analysis, BASCHE et al (2014) found that nitrous oxide emissions are increased by integrating legume catch crops in crop rotations. However, they also concluded that more annual measurements are needed, as short-term effects are partly offset later in the subsequent crop.

So far, there is limited knowledge regarding the effect of legume cultivation on soil carbon stocks. Research in this area takes a long time because the small relative changes can only be determined with confidence over periods of more than 10 years. The cultivation of grain legumes is more likely to lead to soil carbon loss due to the lower C input compared to cereals (PLAZA-BONILLA et al., 2016). In their meta-analysis, POEPLAU & Don (2015) did not find a significant difference in the effect of catch crops with and without legumes on soil carbon stocks, but they could show that catch crops generally have a positive effect on carbon stocks. This effect can compensate for the negative effect of grain legumes on soil carbon stocks (PLAZA-BONILLA et al., 2016).

The effects of climate change on greenhouse gas emissions will also become increasingly important in the future. For example, LAM et al. (2012) showed that the increase in atmospheric CO_2 concentration leads to a stronger fixation capacity of legumes because both the number and mass of root nodules and the nitrogenase activity increase. On the one hand, this would increase the fertiliser substitution capacity, but could also lead to an increase in direct and indirect nitrous oxide emissions and N leaching from the residuals. Research should therefore increasingly focus on the interaction between climate protection and climate adaptation.

Economic effects of legume cultivation

Since forage legumes play only a small role in conventional arable farming and are generally not cultivated as the main crop, there are few studies on the economic effect of their cultivation. Therefore, the state of knowledge on the economic impact of growing large-grained legumes in conventional agriculture is summarised below. Furthermore, some authors point out the importance of marketing structures for the profitability of legume cultivation (KEZEYA SEPNGANG et al., 2018; PREISSEL et al., 2017). However, apart from analyses of the feed value, no systematic analyses on this subject area are available, so that the following literature evaluation is limited to the internal competitiveness at farm level.

Basic competitiveness of legumes

PREISSEL et al (2015) used work from several European countries in a meta study to compare the gross margins of legumes with those of cereals and rapeseed. It was found that legumes often have lower gross margins than non-legumes. The deficit was a maximum of 580 € ha^{-1}.

Soybean however showed advantages over cereals in some studies. In Rhineland-Palatinate (RIEDESSER, 2012) and southern France (MAHMOOD, 2011), the gross margins of soybean were up to €200 ha^{-1} higher than those of cereals. Studies by the Bavarian State Institute of Agriculture (LfL) showed that soybean can be grown competitively with wheat, grain maize, and winter rape when grown under contract and achieve gross margins of up to 600 € ha^{-1} higher than those of faba bean and blue lupin (*Lupinus angustifolius* L.). The reason for the greater competitiveness of soybean compared to other grain legumes is that its market price is about twice as high. Corresponding studies of complete crop rotations with winter wheat, stubble wheat and winter oilseed rape showed that the total contribution margin increases by about 20 € ha^{-1} if soybean is integrated into the crop rotation (LFL, 2015).

Only individual studies from Poland (LMC international, 2009), Germany (ZILLES, 2010) and Finland (PELTONEN-SAINIO and NIEMI, 2012) showed higher gross margins for pea and faba bean than for cereals. Most studies showed considerable gross margin deficits of 300 to 500€ ha^{-1} compared to cereals. Relatively competitive crops such as wheat and maize were assumed as reference crops. However, legumes generally have to compete with the weaker crop rotation crops such as second wheat crops (wheat after wheat). Besides lower gross margins, there are usually also significantly greater volatility in the gross margins for legumes due to yield fluctuation. For this reason, VON RICHTHOFEN et al. (2006b) see agronomic impacts as the primary reason for the cultivation of legumes.

PREISSEL et al. (2017) carried out model calculations on the economic viability of legume cultivation with and without consideration of previous crop values for five regions in Europe (Brandenburg in Germany, Calabria in Italy, eastern Scotland, western Sweden, southern Romania). Without taking pre-crop effects into account, the gross margins of legumes were competitive with alternative crops only in Sweden, England and Romania. For Brandenburg, a gross margin deficit of 300 to 320 € ha^{-1} was reported. Again, the main reason for the competitive disadvantage was the lower yields of legumes compared to alternative crops, which usually cannot be compensated by higher prices. Taking into account the pre-crop value of legumes, the competitiveness of legumes increased by 120-300 € ha^{-1}.

The overall conclusion is that legumes are often not competitive. However, some studies show that soybean cultivation in particular can be competitive where the preceding crop is taken into account. The value of the legume as a preceding crop is determined by the benefits for the subsequent crops in the form of higher yields and reduced costs in terms of fertilisation, plant protection and soil cultivation (WEITBRECHT AND PAHL, 2000; Schäfer, 2013). For this reason, many scientific papers in the field of legume economics deal with the preceding crop value. In the following, the results so far are presented.

Analyses of the previous crop value of legumes

Table 2 summarises the work done so far on the monetary value of previous crops – their values vary considerably between the various studies, ranging from 100 to 500 € ha^{-1}. The main reason for this considerable range is primarily differences in the following assumptions:

1. Increased yield of the subsequent crop: Most studies showed an increase of 0 to 1.5 t ha^{-1} in yield of the subsequent crop compared to wheat as the pre-crop (ALBRECHT & Guddat, 2004; Alpmann & Schäfer, 2014; Zerhusen-Blecher ET AL., 2018). LÜTKE-ENTRUP et al. (2005) showed significantly higher yield advantages for the subsequent crop at individual trial sites with up to 2.5 t ha^{-1}. Some authors also showed small additional yields of the second succeeding crop after legumes in the range of 0.1 to 0.2 t ha^{-1} (ALBRECHT & GUDDAT, 2004; Alpmann ET al., 2013).
2. Price assumptions for the subsequent crops: Considerable differences in the monetary value of the preceding crop effect from very different price assumptions. Here, the range in cereal prices extend from 100 € t^{-1} for barley (ALBRECHT & Gudda, 2004) to 250 € t^{-1} for wheat at Alpmann ET al (2013).
3. N saving of the subsequent crop: In most studies, a N-supply from the legume for the succeeding crop of 0 to 25 kg N ha^{-1} was assumed (ALBRECHT & Guddat, 2004; Alpmann & Schäfer, 2014; Zerhusen-Blecher ET AL., 2018). To some extent, the price assumptions for monetary valuation also differed considerably, ranging from 0.5 € per kg nitrogen (ALBRECHT & Guddat, 2004) to 1 € per kg nitrogen (Alpmann & Schäfer, 2014).
4. Savings on pesticides in the subsequent crop: Most of the authors did not assume that there would be savings in pesticide costs for the succeeding crop. Only RICHTHOFEN et al (2006a) and ALPMANN & Schäfer (2014) considered savings in fungicide use in the subsequent crop of up to 50 € ha^{-1}, where cereals were used as reference crop.
5. Savings in soil cultivation: Only four studies considered potential savings in tillage of the subsequent crop due to an improved soil structure/soil fermentation (SCHÄFER & Lütke-Entrup, 2009; Alpmann ET al., 2013; Preissel ET al., 2015; Zerhusen-Blecher ET al., 2018). The absolute level of the potential savings ranged from 23 € ha^{-1} (ZERHUSEN-BLECHER et al., 2018) to 125 € ha^{-1} (LÜTKE-ENTRUP et al., 2005).

Table 2. Results of analyses of pre-crop effects

Study	Additional yield of 1st crop after legume (t ha^{-1})	Nitrogen saving (kg N ha^{-1})	Pesticides saving (€ ha^{-1})	Tillage saving (€ ha^{-1})	Pre-crop value (€ ha^{-1})
Albrecht and Guddat (2004)	0.9	5 – 24	n.a.	n.a.	118 – 138
Lütke-Entrup et al. (2005)	0.05 – 2.5	0 – 20	5 – 24	n.a.	98 – 380
Richthofen et al. (2006)	0.05 – 0.1	30	35	n.a.	152 – 204
Alpmann et al. (2013)	0.63	27	n.a.	35	>244
Alpmann and Schäfer (2014)	0.5 – 1.5	5 – 35	0 – 50	20 – 60	127 – 471
Preissel et al. (2017)	0.5 – 1.5	23 – 31	<50	70 – 125	160 – 300
Zerhusen-Blecher et al. (2018)	0.66 – 0.75	28 – 32	n.a.	23 – 42	155 - 188

The studies show considerable variation in economic competitiveness. A look at the German regional statistics confirms that this is often caused by regional differences. At the district level, the yield ratios of wheat to faba bean fluctuate between 1:0.3 and 1:0.7 on average over the years 2012 - 2016. Assuming that the ratio of costs between locations remains more or less constant, it can be assumed that competitiveness varies greatly from region to region.

Recommendations and future research needs

Despite economically favourable previous crop effects and beneficial environmental aspects, farmers are only open to increased legume cultivation if it is economically attractive. Therefore, the future priority should be to help overcome existing obstacles to the expansion of cultivation. Besides crop optimisation strategies, sustainable legume cultivation systems particularly require the consideration of phytopathological aspects and the breeding and provision of resistant varieties.

The expansion of legume cultivation can only succeed if newly created knowledge is transferred to agricultural practice and implemented accordingly. To this end, workshops and seminars as well as advisory services must be intensified at all levels of the agricultural sector. The demonstration networks soybean, pea/bean, lupin, and forage legumes will play an important role in carrying out the following tasks: (a) support of the internet platforms, (b) information and contact exchange, (c) cultivation advice, (d) participation in the establishment of value chains, (e) coordination of beacon projects, and (f) identification and demonstration of research needs.

In future, priority should be given to initiating and financing projects that are likely to contribute to a significant expansion of legume cultivation. It is also necessary to adapt the duration of the processing period to the specific questions. For example, to achieve substantial results in the field of crop rotation research, project durations of more than three years are required. New projects should preferably be implemented within interdisciplinary research networks and in close exchange with the respective demonstration networks. For example, longer-term transdisciplinary projects on crop rotation research could be established at different locations in Germany. On-farm research approaches of the demonstration networks or in "landscape laboratories" with farm networks can be linked and scientifically accompanied with economic research under consideration of greenhouse gas emissions and biodiversity measures.

The priority research needs in the areas of crop production, plant protection, biodiversity, climate protection and economics are listed in Table 3.

Table 3. Research needs for the effects of integrating legumes in crop rotations.

Subject area	General conditions	Urgent research needs
Plant production	Many important agronomic questions concerning the cultivation of grain legumes and their integration into crop rotations have already been answered by previous research projects. In particular, the magnitude of the preceding crop effect of legumes is sufficiently described. However, research gaps still exist in the field of breeding improvements, optimisation of cultivation methods and development of new food and feed products.	Improvement of abiotic and biotic stress tolerance (e.g., cooling tolerance in soybean, winter hardiness in winter forms of faba bean and pea). Increasing the yield security of legumes by breeding improvements in disease and pest resistance and weed suppression. Reduction or elimination of antinutritional factors and other value-reducing ingredients. Determination of the intra-species variability for nitrogen fixation performance. Promotion of measures and practices to control seed-borne pests of grain legumes. Dealing with the topic "legume fatigue" in crop rotations (e.g., possible cultivation frequency of legumes, interactions between different legume species and with other crop species). Assessment of leguminous catch crops or catch crop mixtures in terms of preceding crop value and ecosystem services (e.g., nitrogen fixation, nitrogen utilisation and nitrogen leaching) Development and testing of innovative cultivation methods for grain and forage legumes (e.g. crop rotation and cultivation management as well as integration and further development of intercropping systems) to promote the development of economically promising leguminous-based food and feed products.
Plant protection	If the proportion of legumes in the crop rotation is increased, an increased occurrence of leguminous-specific harmful organisms can be expected. This problem is exacerbated by the decreasing availability of chemical plant protection products. By concentrating on a few active substances to control harmful organisms and weeds, an increased development of resistance can also be expected.	Methods development for the application of seed treatment products to control soil-borne harmful fungi (e.g. *Pythium* spp., *Rhizoctonia* spp., *Aphanomyces* spp., *Sclerotinia* spp.) and *nematodes (e*.g. *Meloidogyne* spp., *Pratylenchus* spp., *Heterodera* spp.). Development and testing of effective measures and methods to control animal pests such as pea moth (*Cydia nigricana*), pea gall midge (*Contarinia pisi*), bean and pea beetles (*Bruchus rufimanus*, *Bruchus pisorum*) and leaf beetles (*Sitona* spp.). Development and use of non-chemical methods for regulating and controlling fungal pathogens (e.g. *Ascochyta* spp., *Uromyces viciae-fabae, Peronospora* spp., *Botrytis* spp. and *Colletotrichum* spp.). Development of forecasting methods and decision-making aids for the use of plant protection products based on the damage threshold principle.
Biodiversity	In general, there is still a need for research on the effects of integrating legumes in crop	Breeding of legumes for "pollinator-friendliness" and evaluation of existing varieties in the cultivation system in terms of providing food resources for pollinators (i.e. do the crops

	rotations on biodiversity. Whether and if groups of organisms are promoted has not been sufficiently investigated. As a result, little is known about the ecosystem services of these organisms in legume cultivation itself or in the surrounding agricultural landscape.	flower during cultivation and if so, does harvesting take place during the main flowering period?). Cataloguing the groups of organisms (trophic groups and taxa) associated with the respective arable crops and cultivation systems with and without legumes. Agro-ecosystem studies on the impact of legumes in farming systems on biodiversity from field to landscape scale. Pre-crop and neighbourhood effect of legumes on herbivores and predators. Quantification of ecosystem services (in particular natural pest control, pollination, soil fertility) provided by legume cultivation over several spatial scales (field, farm, landscape). Agronomic and socio-economic valorisation of ecosystem services provided by legumes.
Climate protection	Previous research on greenhouse gas emissions in arable farming often focused strongly on individual crop rotation systems. However, legumes have an impact on the entire crop rotation, which is the strongest argument for their cultivation. There is considerable need for research on the effect of legume integration in crop rotations on their overall greenhouse gas balance. An even better optimised consideration of previous crop values and crop rotation effects, especially in fertilisation planning, offers potential for climate protection.	Impact of legume integration into crop rotations on soil carbon stocks, nitrous oxide emissions and nitrate leaching from legume nitrogen during nitrogen transfer to the first and second subsequent crop. Possibilities for optimising the nitrogen transfer to the subsequent crops and thus, saving mineral fertiliser. Development of practical approaches for optimised potential savings of nitrogen fertilisers in the subsequent crops of legumes.
Economics	From an economic point of view, it is important that the economic evaluation is carried out according to uniform standards to obtain meaningful and trustworthy results.	Systematic recording of crop rotation effects on farms. Generation of information on the economic viability of legume cultivation under practical conditions (e.g., through networks of pilot farms)

Conclusions

Despite the many positive agronomic and agro-ecological effects attributed to legumes, their share of arable land in Germany is still small. The reasons often given for this are insufficient yield security, gaps in plant protection, legume fatigue with a higher proportion in crop rotations, and a lack of profitability. For a comprehensive evaluation of the advantages and disadvantages of integrating legumes in crop rotations, however, there is a lack of results on (1) seed treatment and plant protection measures as well as a possible reduction of plant protection applications in subsequent crops, (2) effects on biodiversity as well as agronomic and socio-economic evaluations of the ecosystem services provided by legumes, and (3) effects on soil carbon stocks, nitrous oxide emissions and nitrate leaching in the entire crop rotation. Only when these issues have been clarified, it will be possible to expand the area under legumes and to make a reliable economic assessment of the integration of legumes in crop rotations.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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