# Legumes Translated Deliverable Report

## Deliverable 5.2

## Legumes Translated Development Guide: Multi-criteria guidance on developing legume cropping

Due date: 10/2021

Project start date: 1 November 2018

Duration: 42 months

Work package: Environmental performance and multi-criteria validation (WP5)

Work package leader: Jens Dauber, TI

Relevant task: Multi-criteria validation (Task 5.2)

Relevant task leader: Moritz Reckling, ZALF

Nature of deliverable: Report

Dissemination level:  Public (PU)

Legumes Translated (Translating knowledge for legume-based farming for feed and food systems) has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 817634

## Objectives of the tasks supporting the deliverable

Improving the environmental performance of cropping and farming systems and ecosystem service (ESS) provision is essential to long-term viability of value chains. Following the Common Classification of Ecosystem Services (CICES), the compilation of knowledge of actor groups and thematic networks on cropping systems and value chains in WP2 will be supported with expert guidance in WP5 focused on biodiversity and ESS impacts, such as effects of cultivation practices, pollination effects, and maintaining soil fertility. In conjunction with Task 3.4, validation of knowledge in Transition Networks will support the identification of options to improve ecosystem service delivery. The findings will be reported in Development Guides and contribute to Practice Abstracts. Within actor groups and transition networks, the objectives of WP5 are to:

1. identify constraints that impact on crop environmental and ESS performance;
2. identify potentials to improve environmental/ESS performance of cropping;
3. provide expert support to the synthesis of knowledge;
4. support the Transition Networks with existing knowledge on environmental effects; and
5. identify options to promote biodiversity and ecosystem service delivery in value chains.

The work reported here is covered by one task: Task 5.2 (led by ZALF, involving all actor group representatives).

Within task 5.2 (Multi-criteria validation), a multi-criteria validation of legume based cropping systems is conducted using the interactions within actor groups and transition networks. This will provide multicriteria expert guidance on the validation and communication of potential alternative strategies. This uses an integrated approach to the compilation and integration of knowledge on selected environmental (nitrogen fertiliser use, nitrate leaching, nitrogen oxide emission, crop diversity) and economic (standard gross margin, gross margin with legume subsidies, gross margin with legume price according to feed value, gross margin with carbon tax) impacts as well as production-related impacts (yield stability, protein output, energy output) to evaluate legumes in crop rotation. Since the variability of yields is widely regarded as a barrier, knowledge on the yield stability will be compiled in the validation of systems for farmers. Results will be used by the actor groups and transition networks (Tasks 3.1 and 3.4) to identify cropping systems with low tradeoffs between economic and environmental impacts and to point to optimum cropping options.

This deliverable report will comprise the Legumes Translated Development Guide on knowledge on agronomic and environmental effects and on economic impacts to examine trade-offs. This will provide multi-criteria expert guidance on the validation and communication of potential alternative strategies.

## Activities undertaken

Several steps were undertaken to perform the multi-criteria assessment of cropping systems with and without legumes. The assessment approach was presented to the project partners and actor groups during the first consortium meeting in November 2018, updates were provided at the consorium in September 2019 and first results presented in

2020. The approach that is built on previous work was adapted to the objectives of Legumes Translated and a set of 11 assessment indicators were developed and aligned to the interests of the actor groups. A data query designed together with TI for the compilation of cropping systems and introduced to the actor groups. Open questions were discussed with the actor groups and an iterative process of data checking that was jointly performed with the data providers followed the data collection. The multi-criteria assessment was performed and the results were provided to the participating actor groups. Nine actor groups participated in the data query and provided data on regional cropping systems with and without legumes: Bulgarian Legumes Network (represented by ABI), German Soybean Association (represented by LTZ), Schwäbisch Hall Producers (represented by BESH), Soybean Cultivation Group in Southeast Europe (represented by IFVC, Europe Soya Value Chain Development Group (represented by DS, German Pea and Bean Network (represented by LLH), Brandenburg Farmers' Network (presented by ZALF), The Irish Grain Legumes Group (represented by AST and Teagasc) and SRUC Dairy Protein Group (represented by the SRUC). From these nine actor groups 22 pairs of cropping systems with and without legumes were provided. Feedback on the first assessment results was collected and an online event for further discussions was held with all participating actor groups. Additional remarks from the actor groups were integrated in the assessment. To clarify open questions on the methodology a report of methods was composed and provided to the actor groups. Actor group representatives checked the validity and plausibility of the final results together with regional experts. The results of the assessments were analyzed in detail and compiled in this deliverable report.

**Results**

The diverse network in Legumes Translated allowed us to compile 22 pairs of cropping systems with and without legumes that enabled a multi-criteria impact assessment. A comprehensive set of 11 assessment indicators in three impact areas were designed and aligned to the actor groups' interests.

Results from the assessment across all regions can be summarized as follows:

On average, crop rotations with legumes reduced nitrous oxide emissions by 21% and 26% and nitrogen fertiliser use by 26% and 45% in arable and forage systems, respectively. Nitrate leaching was similar in the arable cropping systems and was increased by 11% in the forage cropping systems with legumes. The average crop diversity index was 44% lower in arable cropping systems without legumes and similar in forage cropping systems with and without legumes. While protein output was increased by 13% and 5%, energy output was reduced by 10% and 9% in arable and forage systems. There was no evidence for an increase or decrease in yield stability for legume-supported crop rotations. The effect on gross margins of introducing legumes was variable and site specific. Consideration of the full economic value of the crops as feed, subsidies for legumes, and the application of carbon taxes increased the relative performance of the legume-supported systems.

Soybean was most commonly integrated in legume-supported cropping systems in southern and central-east Europe. Soybean was also used in some regions in central-west Europe. These soybean-supported cropping systems were mostly more profitable than their reference cropping systems and also had considerable advantages in the protein yield. Moreover, the environmental indicators showed also benefits for the soybean systems. Arable cropping in north-western Europe included either faba bean or pea. The economic performance of these systems were mostly similar to their reference systems and improved when the legume feed value, subsidies and carbon taxes were included. All nitrogen-related impacts were reduced, protein output increased, while energy output was generally unaffected. Faba bean or pea suppoted cropping systems in central-west and eastern Europe showed also advantages in the environmental impact area and for the protein yield. They however had lower gross margins compared to their reference systems.

Forage cropping systems from southern Scotland and north-eastern Germany showed considerably reduced nitrogen fertilisation and nitrous oxide emissions when forage legumes such as alfalfa or clover in mixtures with grass were included. However, the introduction of alfalfa to rotations in both regions resulted in lower gross margins compared to the non-legume reference rotations.

Considerations of the single case studies allowed an identification of cropping systems with low tradeoffs between the analyzed impact areas of economy, environment and production and validated potential alternative strategies. Due to the economic advantages and high protein output, especially soybean-supported systems were found to have low tradeoffs or showed even win-win situations.

**Conclusions**

Legumes can considerably increase the sustainability of agro-ecosystems and make valuable contributions to a range of ESS. A holistic cropping system perspective is needed to fully evaluate the complex and range of impacts of legumes and get a realistic view on their contributions to farming systems. Due to the currently low cropping shares of legumes in European agricultural systems, experiences and practice-based data on legume-supported cropping systems are scarce. However, the range of legume-experienced actors in Legumes Translated allowed us to compile the knowledge and experiences of these experts and provided the ideal basis for assessing the role of legumes in crop rotations of real farm situations.

The comparisons between reference cropping systems without legumes and legume-supported systems showed that the latter had advantages in the environmental impact area with lower nitrogen fertiliser use, lower nitrous oxide emissions, increased crop diversity and in some cases also decreased nitrate leaching. Economic benefits were found particularly in soybean-supported systems and rotations with high-yielding legumes. The economic performance clearly increased when considering the legume feed value, subsidies, and carbon taxes. The common negative perception that legumes increase the production risk due to greater yield instability was not confirmed in the assessment at cropping system scale. Protein output was found to be increased in legume-supported systems which displayed the potential for contributing in part to Europe's protein self-sufficiency, however with a trade-off for lower food or feed energy yields.

The analysis outlined several cases where legumes led to win-win situations or only minor trade-offs between the evaluated impact areas and presented potential alternative cropping strategies that can be communicated within and beyond the actor groups. Some management changes and crop design optimisations such as the consideration of positive pre-crop benefits on yield and fertilisation planning could further strengthen the positive effects from legume cropping. Moreover, various external factors can also enhance the positive impacts and reduce potential economic disadvantages from legume rotations. Policy support either via direct payments within the voluntary coupled support (VCS), country or region specific environmental payment schemes such as the support for "diverse crop rotations" with a minimum share of legumes in some German states or indirectly via financially valuing ecosystem service provision of legumes is an important element in fostering legume profitability. The development of new market outlets and value chains for European legumes will help correct the current economic under-valuation of legumes and could increase the market prices. Additionally, advances in legume breeding and improvements in agronomy can improve the productivity and performance in legume cropping.

This work on the multi-criteria assessment of project partners' cropping systems is an example of the project's co-learning cycles working to combine the insights of differing actor groups within a robust analytical framework. It supported the illustration and reflection of legume impacts in tangible indicators as well as the communication in the case study regions on opportunities and constraints of legume-supported cropping systems.

Further plans for dissemination include the hosting of a webinar for the Legumes Translated consortium for the purpose of sharing and discussing the results based on the presentation of the summarized findings in this deliverable report. Subsequently, the translation and processing of the results in further Legumes Translated publishing formats is planned in order to break down the detailed findings and make them accessible for a broader range of stakeholders. In terms of the academic dissemination a scientific paper on the findings of the multi-criteria assessment is planned as well as a joint conference contribution with all data providing partners in the Landscape 2021 conference.[1]

Inka Notz, Moritz Reckling

26 May 2021

[1] https://www.landscape2021.org/frontend/index.php.

# Legume Translated practice guide

# Multi-criteria guidance on developing legume cropping

**Prepared by:**

Inka Notz[1], Sheila Alves[2], Thorsten Haase[3], Paul Hargreaves[4], Michael Hennessy[2], Anelia Iantcheva[5], Jürgen Recknagel[6], Leopold Rittler[7], Johannes Schuler[1], Kairsty Topp[4], Marjana Vasiljević[18], Fritz Wolf[9], Moritz Reckling[1]

[1]Leibniz Centre for Agricultural Landscape Research (ZALF), Germany

[2]Teagasc, Ireland

[3]Landesbetrieb Landwirtschaft Hessen (LLH), Germany

[4]Scotland's Rural College (SRUC), United Kingdom

[5]AgroBioInstitute, Bulgaria

[6]Agricultural Technology Centre Augustenberg (LTZ), Germany

[7]Donau Soja, Austria

[8]Institute of Field and Vegetable Crops, Serbia

[9]Landwirtschaftlicher Beratungsdienst Schwäbisch Hall e.V., Germany

May 2021

Legumes Translated (Translating knowledge for legume-based farming for feed and food systems) has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 817634

**Legumes Translated**

Legumes Translated (Translating knowledge for legume-based farming for feed and food systems) is an international research and development project funded by the European Union through the Horizon 2020 Programme under grant agreement number 817634. The Legumes Translated research consortium comprises 17 partners in 9 countries.

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Please cite this report as follows:

Notz, I., Alves, S., Haase, T., Hargreaves, P., Hennessy, M. Iantcheva, A., Recknagel, J., Rittler, L., Schuler, J., Topp, K., Vasiljević, M., Wolf, F., Reckling, M., 2021. Multi-criteria guidance on developing legume cropping. Legumes Translated. Available from www.legumestranslated.eu

## Contents

# Introduction

Legume-supported cropping systems can improve environmental performance as well as resource-efficiency of farming and contribute to a higher level of protein self-sufficiency in Europe. The notable contribution of legumes to ecosystem services (ESS) by offering benefits in the categories of provisioning, supporting and regulating services, appears to be widely understood in the scientific community. However, considering current agricultural practices in Europe, there seems to be an unbroken trend in specialisation in cropping systems. Most systems are dominated by cereals which can cause a range of negative effects on the environment and climate via nutrient losses, high energy use, greenhouse gas (GHG) emissions, and further detrimental impacts. At the same time the share of legumes in the European arable area and the integration in cropping systems is rather negligible and there seems only a very slow inversion of this trend over the last decades. Mostly, the lower profitability of legumes in comparison to other crops is named as a reason for the minor proportion of arable land used for legume crops.

There is, therefore, a need to examine  the multiple impacts of legumes on crop rotations and make knowledge on the effects of legumes accessible to a broader range of stakeholders. Ann impact assessment of the effect of integrating legumes into cropping systems is an effective tool as it synthesizes scientific evaluations by illustrating and informing on effects within the included impact areas. Diverse approaches have already been applied for evaluating the integration of legumes in cropping systems. A close involvement of regional actors who are engaged in legume cultivation and the integration of cropping systems according to their experiences and stated relevancies can expand previous research work and strengthen efforts for disseminating potential alternative cropping strategies.

The European multi-actor project Legumes Translated provides the ideal frame for this research concept, including a range of legume-experienced actors all over Europe and following the approach of compilation and validation of existing practices and enabling thereby, the empowerment of innovators and lastly the dissemination of innovative legume-supported cropping systems.

Therefore, the main objective of the work reported here was to compile relevant cropping systems with and without legumes from practice-based project partners all over Europe, to develop a set of tangible indicators and to assess the systems providedto illustrate effects of legume integration in cropping systems, within the so-called multi-criteria assessment. Additionally, the case study backgrounds with legumes' roles were elaborated by considering actual cropping shares in order to outline future potential for legume cultivation.

17 case study regions[2] within nine countries were considered, encompasing Ireland, Scotland, Germany, Austria, Italy, Serbia, Bulgaria, Romania and Ukraine.[3] The multi-criteria assessment was based on data on cropping systems provided in a data gathering process between September 2019 and March 2020.

[2] Case study regions refer to the local areas in which the data providing project partners – the actor groups - are active and were categorized within the NUTS-2 regions.

[3] An overview on the included countries and regions from the data providing actor groups is provided in Annex I.

This report firstly outlines the materials, referring to the data source and the collection. Then the methodological approach of the multi-criteria assessment is described, before actually applying the framework in the case study regions. Lastly, the results are discussed and conclusions are drawn.

## Materials and methods

### Data source

In order to explore legume-supported cropping systems in comparison to farming practice without legumes, data on crop rotations and crop management was needed to be provided from the project partners. To understand the background of the collected data, it is useful to consider briefly the project approach of LT.

Legumes Translated is an EU a thematic network that links research- and practice-based knowledge on the basis of a 'bottom-up' multi-actor approach. The core of this project concept is based on 14 groups of farmers and other innovators - actor groups - within nine European countries.[4] These actor groups have different foci and interests in regionally adapted legume species.[5] Experiences and practice in legume cultivation is therefore a common feature of all actor groups, so that the challenge of limited available information on legume cropping caused by the low cultivation shares within Europe can be handled with the reflection of practical work in legume cultivation from the actor groups. The objective of the data collection was hence to make use of these valuable sources and innovative actors to capture their experiences on locally relevant and existing practices. Thereby, the basis of the data is formed by interests of practitioners from different European regions, ensuring the connection to actual farming and allowing a participatory assessment approach.[6]

### Data collection

The practical method to compile the data needed was a structured data query that was sent out to all actor groups and processed between September 2019 and March 2020.The objective of the data query was the determination of conventional cropping systems with and without legumes. A cropping system involves crop rotation, crop management and production orientation.[7] Following Castellazzi et al., a crop rotation is defined as a fixed sequence of crops that is grown in cyclical repetition in a particular field.[8] Crop

[4] Murphy-Bokern, D., Dauber, J., Rittler, L., Krön, M., Schuler, J., Reckling, M., Willer, H., Haase, T., Schaumann, C., Lindstöm, K., Zimmer, C., Dewhurst, R., Barkas, D., Recknagel, J., Iancheva, A., Petrovic, K., Alves, S., O' Donovan, T., Orestis, R., Watson, C. 2019. Translating knowledge for legume-based farming for food and feed (Legumes Translated). Presented at the European Conference on Crop Diversification (ECCD), Budapest: Zenodo. doi: 10.5281/ZENODO.3598522.

[5] An overview on all actor groups within Legumes Translated is presented in Annex II.

[6] The actor groups were involved in the data collection (including an iterative and interactive data checking process, see data collection and Annex II), selection of the assessment indicators, discussion and calibration of results and final communication and dissemination of the analysis findings.

[7] Reckling, M., Hecker, J.-M., Bergkvist, G., Watson, C., Zander, P., Stoddard, F., Eory, V., Topp, K., Maire, J., Bachinger, J. 2016. A cropping system assessment framework—evaluating effects of introducing legumes into crop rotations. Eur. J. Agron. 76, 186–197. doi: 10.1016/j.eja.2015.11.005.

[8] Castellazzi, M.S., Wood, G.A., Burgess, P., Morris, Jl., Conrad, K.F., Perry, J.N. 2008. A systematic representation of crop rotations. Agricultural Systems 97, 26-33. doi: 10.1016/j.agsy.2007.10.006.

management had to be determined for each crop and included cropping inputs such as seeds, fertilisation and plant protection, outputs such as grain and straw yield as well as the particular management, including tillage, fertiliser and plant protection intensity, harvesting method, cover crops and further management options. The information on the cultivation techniques was intended to include adapted management depending on the pre-crops (e.g. nitrogen fertiliser application) and the pre-crop effects on yield.

Besides the specification of crop rotation and management, the data query collected information on site characteristics and long-term yield data of the respective crops in the crop sequences.

The region-specific crop rotations with cultivation techniques were provided as input from the members of the actor groups that could be scientists, farmers, advisors or other stakeholders. It was essential that the compiled cropping systems represent local practices and are of interest to the actor groups. The stakeholders could thereby refer to data from official statistics, single farm practices or research experiments. One rotation without legumes and at least one rotation with legumes as the alternative option was specified per region. Various alternative options with legumes were also possible.

In the course of the data collection, several practical issues became apparent and an iterative process of data gathering and checking was initialized, in order to meet the necessary data structure.[9]

### Case studies

From the 14 actor groups enclosed in LT, nine groups provided data for the multi-criteria assessment. Figure 1 shows the regions that were covered by the participating partners from LT, including their shares of arable land used for grain legumes.[10] Diverse cropping systems across Europe involving agro-climatic zones from the Atlantic North to the Eastern Continental zone were included.

[9] An overview on issues tackled within this process is presented in Annex III.
[10] Due to limited data availability only arable land used for grain legumes and not also forage legumes is shown.

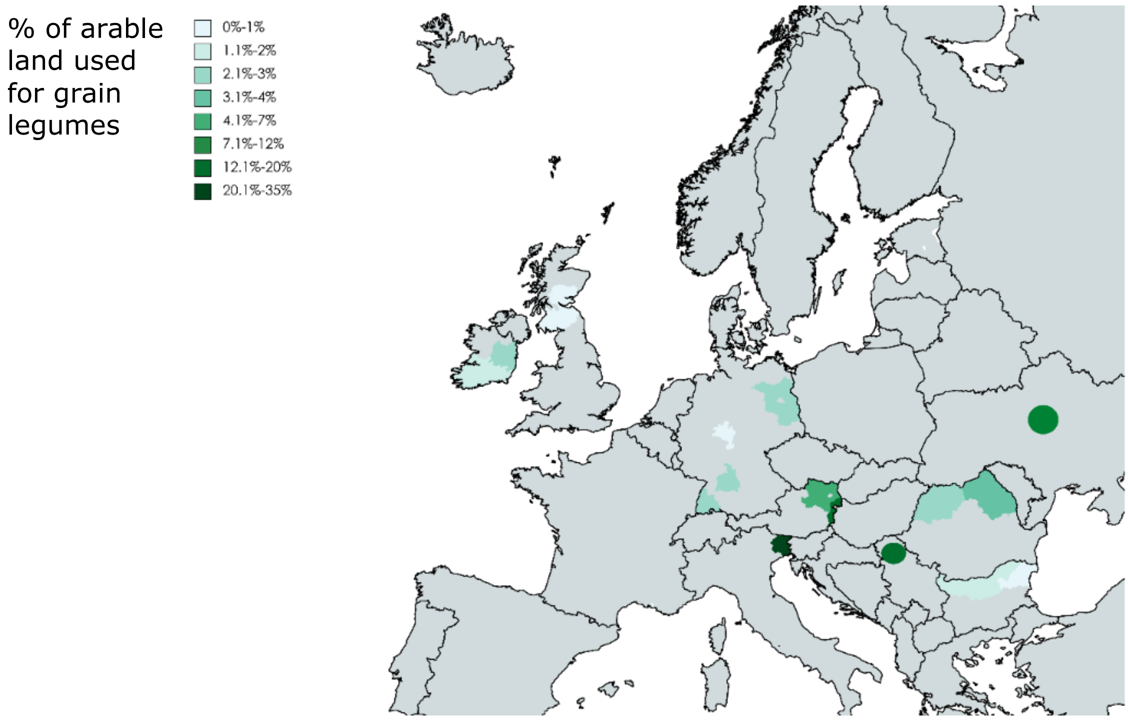


Figure 1 Case study regions across Europe - NUTS 2 regions (regions in Serbia and Ukraine marked separately) – with proportion of arable land used for grain legumes in 2019.[11]

An overview of included countries with specific regions, their site characteristics and crop choices for the case study is presented in Table 1. To highlight the relevance of grain legume cropping in the respective countries, the percentage of grain legumes in the arable land area and the absolute cultivated area is also integrated.

[11] Calculations based on data from Eurostat. European Commission, Brussels, Belgium. https://ec.europa.eu/eurostat; State Statistics Service of Ukraine. https://ukrstat.org/en/operativ/menu/menu_e/cg.htm; State Service of Ukraine Geodesy, Cartography and Cadastre.

Table 1. Site characteristics, crops and grain legume production in the case study regions

| Country | Region | Soil texture | Annual rain fall [mm] | Non-legume crops[1] | Legume crops[1] | % of grain legumes[2] | Area in 1000 ha[2] |
|---|---|---|---|---|---|---|---|
| *Arable cropping systems*[3] | | | | | | | |
| Central-eastern Europe | | | | | | | |
| Bulgaria | BG 31 | Sandy loam[4] | 550 | WW, GM, SF | FP | 1.72 | 13.9 |
| | BG 32 | Sandy loam[4] | 575 | WOR, WW, SF, GM | SY | 1.16 | 7.7 |
| | BG 33 | Sandy loam[4] | 575 | WOR, WW, SF, GM | CB | 0.80 | 6 |
| Romania | RO 11 | Sandy loam[4] | 531 | GM, WW | SY | 2.41 | 21.3 |
| | RO 21 | Sandy loam[4] | 430 | GM, SF, WW | SY | 3.36 | 43 |
| Serbia | RS 12 | Sandy loam[4] | 421 | GM, WW | SY | 14.40 | 206.3 |
| Ukraine | Kyiv oblast | Sandy loam[4] | 560 | GM, SF, WW, SF | SY | 10.62 | 140.3 |
| Central-western Europe | | | | | | | |
| Austria | AT 11 | Silty loam[5] | 700 | GM, WW | SY | 16.59 | 26.1 |
| | AT 12 | Sandy loam[4] | 470 | GM, WW, SF | SY | 4.67 | 31.5 |
| Germany | DE 11[6] | Silty loam | 740 | WW, WB, TR, SU, GM | FB, FP | 2.16 | 17.6 |
| | DE 13[6] | Gravel | 550 | GM, WW, WOR | SY | 2.16 | 17.6 |
| | DE 13[6] | Silt | 700 | GM, WW, WOR | SY | 2.16 | 17.6 |
| | DE 40 (soil type 2) | Sandy loam | 510 | WW, WB, WOR, WB | FP, SY | 2.01 | 20.3 |
| | DE 40 (soil type 3) | Sandy loam | 510 | WR, WOR | L, FP | 2.01 | 20.3 |
| | DE 73[6] | Sandy loam | 663 | WOR, WW, SB | FP | 0.85 | 8.6 |
| North-western Europe | | | | | | | |
| United Kingdom | UKM 7[6] | Sandy loam | 753 | WOR, WB, WO, SB | FB, FP | 0.30 | 2.32 |
| Ireland | IE 05, IE 06 | Loam | 900 | WB, WO, WW, WOR, SMB, SO, SFB | FB | 1.95 | 8.1 |
| Southern Europe | | | | | | | |
| Italy | ITH 4 | Silty loam | 1350 | GM | SY | 30.03 | 52.0 |
| *Forage cropping systems*[7] | | | | | | | |
| Germany | DE 40 (soil type 2) | Sandy loam | 510 | WW, WR, SM | AF | - | |
| United Kingdom | UKM 9 | Sandy loam | 1121 | GR, SB, WW | AF, GC, FB, P/B, FP | - | |

[1]AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat; [2]arable land in 2019; [3]cropping systems that only include grain crops were categorized as arable cropping systems; [4]Chernozem, in Bulgaria leached chernozem, in Ukraine podzolic chernozem, in Austria gley chernozem; [5]Pseudogley; [6]due to limited data availability the numbers for this region are based on the NUTS 1 region; [7]cropping systems which include at least one forage crop were categorized as forage cropping systems.

Nine countries are covered, with several regions presented in Austria, Bulgaria, Germany, Romania and Scotland resulting in a total of 17 case study regions. Variations in the relevance of grain legume production are visible with higher legume cropping shares in Italy, Austria, Serbia and Ukraine. In all of these four countries soybean production is most important, representing more than 80% of the cultivated grain legume areas in the Burgenland (AT 11), Italy and Ukraine. Lowest proportions are dedicated for grain legume production areas in Severoiztochen (BG 33), Nordhessen (DE 73) and Scotland. In these examples the share of grain legume production in arable land is below 1%.

Climatic conditions constrain the choice of species, which is apparent in the distribution of included legumes species across the regions. Soybean were included in ten regions and were especially present in the eastern and southern regions. Cool-season grain legumes as faba bean, field pea and lupin were found mainly in the examples from north-western Europe as well as Germany. The latter is marked by the usage of a wide range of legume species.

Forage cropping systems were provided by actor groups interested in mixed farming systems for dairy production and involved next to forage legumes as alfalfa and clover in mixtures with grass, pea-barley mixtures and pea grown in pure stands.

The actor groups specified crop sequences with a minimum of two and maximum of six crops (Table 2, Table 3, Table 4). In terms of the arable cropping systems, 20 non-legume based rotations with at least one or several alternative crop rotations with legumes were given. Concerning the forage cropping systems, two non-legume rotations were provided with several alternative legume-supported rotations for comparison.

Table 2. Crop rotations from case study regions in central-eastern and central-western Europe. Legumes are highlighted in bold.

| Region | +/- legume | Crop 1 | Crop 2 | Crop 3 | Crop 4 | Crop 5 | Crop 6 |
|---|---|---|---|---|---|---|---|
| *Arable cropping systems* | | | | | | | |
| Central-eastern Europe | | | | | | | |
| BG, BG 31 | - | WW | GM | SF | | | |
| | + | **FP** | WW | GM | SF | | |
| | + | WW | SF | **FP** | GM | | |
| BG, BG 32 | - | WOR | WW | SF | GM | | |
| | + | **SY** | WW | SF | WW | | |
| BG, BG 33 | - | WOR | WW | SF | GM | | |
| | + | **CB** | WW | SF | WW | | |
| RO, RO 11 | - | GM | WW | | | | |
| | | GM | WW | **SY** | | | |
| RO, RO 21 | - | GM | SF | WW | | | |
| | + | GM | WW | **SY** | | | |
| RS, RS 12 | - | GM | WW | | | | |
| | + | GM | WW | **SY** | | | |
| UA, Kyiv oblast | - | GM | SF | WW | | | |
| | + | GM | **SY** | SF | WW | | |
| Central-western Europe | | | | | | | |
| AT, AT 11 | - | GM | GM | WW | | | |
| | + | **SY** | WW | GM | | | |
| AT, AT 12 | - | GM | WW | SF | | | |
| | + | GM | WW | **SY** | | | |
| DE, DE 11 | - | WW | WB | TR | | | |
| | + | WW | WB | **FP** | TR | | |
| DE, DE 11 | - | SU | WW | WB | GM | | |
| | + | SU | WW | WB | **FB** | | |
| DE, DE 13 (gravel) | - | GM | GM | WW | WOR | | |
| | + | GM | GM | **SY** | WW | WOR | |
| DE, DE 13 (silt) | - | GM | GM | WW | WOR | | |
| | + | GM | GM | **SY** | WW | WOR | |
| DE, DE 40 (soil type 2) | - | WW | WB | WOR | | | |
| | + | WW | **FP** | WW | WB | WOR | |
| | + | WW | **SY** | WW | WB | WOR | |
| DE, DE 40 (soil type 3) | - | WR | WR | WOR | | | |
| | + | WR | **FP** | WR | WOR | | |
| | + | WR | **L** | WR | WOR | | |
| DE, DE 73 | - | WOR | WW | WW | SB | | |
| | + | WOR | WW | **FP** | WW | SB | |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 3. Crop rotations from case study regions in north-western and southern Europe. Legumes are highlighted in bold.

| Region | +/- legume | Crop 1 | Crop 2 | Crop 3 | Crop 4 | Crop 5 | Crop 6 |
|---|---|---|---|---|---|---|---|
| *Arable cropping systems* | | | | | | | |
| North-western Europe | | | | | | | |
| GB, UKM 7 | - | WOR | WB | WO | SB | WB | |
| | + | WOR | WB | WO | **FP** | WB | |
| | + | WOR | WB | WO | **FB** | SB | |
| IE, IE 05, IE, 06 | - | WB | WO | WW | WB | WOR | WW |
| | + | WB | WO | WW | **FB** | WW | |
| IE, IE 05, IE, 06 | - | SMB | SO | SFB | SMB | SMB | |
| | + | SMB | **FB** | SO | SFB | SMB | |
| Southern Europe | | | | | | | |
| IT, ITH 4 | - | GM | GM | GM | | | |
| | + | GM | **SY** | | | | |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 4. Crop rotations for forage legumes in case study regions in central-western and north-western Europe. Legumes are highlighted in bold.

| Region | +/- legume | Crop 1 | Crop 2 | Crop 3 | Crop 4 | Crop 5 | Crop 6 |
|---|---|---|---|---|---|---|---|
| *Forage cropping systems* | | | | | | | |
| Central-western Europe | | | | | | | |
| DE, DE 40 | - | WW | WR | SM | SM | SM | |
| | + | WW | WR | **AF** | **AF** | **AF** | |
| North-western Europe | | | | | | | |
| GB, UKM 9 | - | GR | GR | GR | SB | | |
| | + | **GC** | **GC** | **GC** | WW | | |
| | + | **GC** | **GC** | **GC** | SB | **FP**/SB | WW |
| | + | **GC** | **GC** | **GC** | SB | **FP** | WW |
| | + | **GC** | **GC** | **GC** | SB | **FB** | WW |
| | + | **AF** | **AF** | **AF** | SB | | |
| | + | WW | **GC** | **GC** | **GC** | SB | |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Within the provided crop rotations the legume appeared either as an additional year in the rotation – expanding the non-legume rotation - or as a replacement for another crop in the rotation without legume. In some cases the rotations were further differentiated, for example, through a change in order of the crops or additional substitutions of crops.

These greater differences in the rotations with and without legumes narrowed the static comparability between the systems, especially the traceability of the legume-specific effects in the comparison. However, the approach of compiling existing practices and the practices that are of interest to the actor groups– which mainly caused the greater differences between the crop sequences – was balanced with methodologically needed restructuring.[12]

**The multi-criteria assessment**

The multi-criteria assessment methodology was built on previous work on the cropping system assessment framework developed by Reckling et al..[13] Whilst the former work included the generation and design of cropping systems, the implementation within Legumes Translated focused on the compilation of practice-based cropping systems and their evaluation. The objective was to assess impacts of changes in cropping systems, especially through the introduction of legume crops. Thereby, a comparison between non-legume cropping systems and legume-supported cropping systems was targeted. Considering the high relevance of legumes' rotational effects, we chose an analysis at the cropping system scale in order to capture legumes' multiplex impacts.[14]

The assessment was based on the calculation of a set of indicators. In order to ensure a more comprehensive analysis, the indicators referred to different impact areas, including economic, environment and climate, and production. This broader view covered legume-specific (e.g. related to nitrogen and protein) as well as unspecific (e.g. gross margins and yield stability) indicators. This should prevent a potential bias towards legumes in the results. Moreover, covering a range of impact areas allowed an illustration of trade-offs as well as synergies between the different criteria. The selection of the indicators was refined using input from the actor groups.[15] Further requirements for the indicators were to be simplicity (understood by all stakeholders) and ease of use producing outputs that could be easily interpreted. In total 11 indicators were integrated in the assessment (Table 5).

By evaluating the cropping systems with the indicators that were discussed with the actor groups, it was targeted to apply an assessment method that is accessible and transparent to the data providers. Thereby it was targeted to provide scientific guidance on the validation and communication of potential alternative cropping strategies within the actor groups. Hence the outputs are considered a transparent transformation of practice-related experiences into synthesised information that helps to discuss different cropping systems, propose legume-supported cropping systems and thereby support stakeholders in decision-making.

[12] Further details on issues within the data gathering are presented in Annex II.
[13] Reckling, M., et al. 2016. A cropping system assessment framework—evaluating effects of introducing legumes into crop rotations. Eur. J. Agron. 76, 186–197. doi: 10.1016/j.eja.2015.11.005.
[14] Preissel, S., Reckling, M., Schläfke, N., Zander, P. 2015. Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. Field Crops Res. 175, 64–79. doi:10.1016/j.fcr.2015.01.012.
[15] Project reports (on actor groups ambitions and descriptions) and joint meetings were used to record information on actor groups'interests and particularly discuss the indicator selection.

Table 5. Indicators and variables used to evaluate cropping systems

| Indicators | Input and output variables |
|---|---|
| *Economy* | |
| Gross margin (standard) | Input: yield, inputs, management operations, prices, costs<br>Output: gross margins in € per ha and year |
| Gross margin (subsidies) | Input: yield, inputs, management operations, prices, costs, subsidies<br>Output: gross margins in € per ha and year |
| Gross margin (feed value) | Input: yield, inputs, management operations, prices, costs, legumes' feeding value<br>Output: gross margins in € per ha and year |
| Gross margin ($CO_2$-tax) | Input: yield, inputs, management operations, prices, costs, fertiliser conversion factor<br>Output: gross margins in € per ha and year |
| *Environment and climate* | |
| Nitrogen fertiliser | Input: N in organic and mineral fertiliser<br>Output: nitrogen fertiliser per ha and year |
| Nitrate leaching | Input: yield, N in organic and mineral fertiliser, N mineralisation from soil, water holding capacity and precipitation in winter half-year<br>Output: nitrate-N leaching per ha and year |
| Nitrous oxide emissions | Input: yield, N in organic and mineral fertiliser, fraction of above-ground residues removed, nitrate leaching<br>Output: Nitrous oxide emission per ha and year |
| Crop diversity | Input: crop species, length of crop sequence<br>Output: Diversity index between 0 (low) and 1.099 (high) |
| *Production* | |
| Yield stability | Input: long-term yield data<br>Output: Coefficient of variation in % |
| Protein output | Input: DM yield, conversion factor crude protein<br>Output: protein yield per ha and year |
| Energy output | Input: DM yield, conversion factor gross energy<br>Output: protein yield per ha and year |

**Indicator calculations**

All indicators except crop diversity were calculated per ha and year at the scale of single crops and subsequently averaged over the whole rotation. This calculation of average values per hectare per year allowed relative comparisons between the rotations of different lenghts.

*Economic indicators*

1. Standard gross margin

As a basis for the economic assessment the standard gross margin (GM) was calculated. The GM of the single crops [€/ha], are calculated with subtracting the total variable costs ($C_{VAR}$) from the revenue of the crop ($R_C$):

$$GM = R_C - C_{VAR}$$

$R_C$ includes revenues from main ($_{MP}$) and by-product ($_{BP}$):

$$R_C = Y_{MP} * P_{MP} + Y_{BP} * P_{BP}$$

with Y as the harvested yield(s) [t/ha] and P as the sale price [€/t] that were communicated by partners.

The total variable costs $C_{VAR}$ include costs of seed ($C_{seed}$) [€/ha], fertilisers ($C_{fert}$) [€/ha], crop protection ($C_{prot}$) [€/ha], variable costs of machinery ($C_{MA}$) [€/ha], where applicable costs of irrigation ($C_{irrig}$) [€/ha], insurance $C_{ins}$ [€/ha] and drying and cleansing costs $C_{drycle}$ [€/ha]:

$$C_{VAR} = C_{seed} + C_{fert} + C_{prot} + C_{MA} + C_{irrig} + C_{ins} + C_{drycle}$$

Labour costs as well as subsidies are not included.

2. Gross margin with subsidies

The standard GM is modified with the inclusion of subsidies following the main Common Agricultural Policy (CAP) instruments supporting legume cultivation. Two from the three instruments that are relevant for legume production in the 2014-2020 period[16] are included in the calculations.[17]

Under Pillar I, the voluntary coupled support (VCS) (Regulation (EU) No. 1307/2013, Art. 52 and 53) is an option for member states to support sectors that are particularly important for economic, social or environmental reasons and experience certain difficulties. Protein crops and grain legumes are included in the range of commodities that may be grant supported.[18] Member states' usage of VCS for legumes differ and are integrated in the calculation where used. The following incentives that take the form of annual payments per hectare from measures shown in Table 6 are considered.

Table 6. Overview on measures within the VCS for protein crops in EU member states included in case studies[19]

| Country | Measure |
|---|---|
| Ireland | Coupled Aid for Protein Crops |
| Bulgaria | Measure for Coupled Support for Protein Crops |
| Romania | Schema de sprijin cuplat în sectorul soiei |
| Italy | Colture proteiche nel Nord Italia (soia) |

In the CAP's Second Pillar, the Rural Development Programme (Regulation (EU) No. 1305/2013)[20] includes support to producer groups, organic farming and agri-environmental-climate measures. All three approaches can potentially be relevant for the support of legumes. Payments derived from agri-environmental-climate measures

[16] European Commission 2018. Report from the Commission to the Council and the European Parliament on the development of plant proteins in the European Union; https://eur-lex.europa.eu/legalcontent/EN/TXT/?uri=CELEX%3A52018DC0757.

[17] Greening is not included in the GM calculation, as in this instrument legume production is conceptualized as one of several possible conditions that have to be met in order to ensure a share of the payments within the first pillar. To include the effects from legume production an assessment on the farm-level would be necessary.

[18] European Union 2013. Regulation (EU) No. 1307/2013 of the European Parliament and of the Council of 17 December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation (EC) No. 637/2008 and Council Regulation (EC) No. 73/2009. Official Journal of the European Union L 347: 608–670.

[19] European Commission 2019. Voluntary coupled support. Review by the Member States of their support decisions applicable as from claim year 2019. In: Informative Note: September 2019.

[20] European Union 2013. Regulation (EU) No. 1305/2013 of the European Parliament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC) No 1698/2005 Official Journal of the European Union L 347: 487-548.

(following Art. 28 of Regulation (EU) No. 1305/2013), which support legume production and are applicable for the rotations from the case studies, are included in the GM calculations according to the states' or regions' specifications.[21]

Payments from VCS ($S_{VCS}$) and agri-environmental-climate measures ($S_{AEM}$) were added to the crop revenue in the GM calculation:

$$GM = R_C + S_{VCS} + S_{AEM} - C_{VAR}$$

All other equations are similar to I.1..

3. Gross margin incorporating feed value

Besides the standard GM and the GM with subsidies, a scenario with modified legume prices is calculated. This feed value price scenario assumes legume selling prices that are equivalent to their actual feed value. With the help of a German feed calculator for pork feed ingredients[22], adapted prices for legumes are provided for the GM calculation.[23] [24] Using current wheat and soybean purchase prices[25], the software calculates the equivalent economic value of other products such as lupin or pea on the basis of their most important contribution to pig feeds – which are the essential amino acid lysine and metabolizable energy.

The legume revenue calculation is replaced with:

$$R_C = Y_{MP} * P_{LFV}$$

with $P_{LFV}$ as the legume selling price assumed to be equivalent to the legume feed value (LFV). All other equations are similar to I.1..

4. Gross margin with carbon tax

Another GM is calculated under the assumption of a carbon tax. The carbon tax is levied on the use of all fossil carbon sources within the manufacture of synthetic nitrogen fertiliser. Emissions through the use of nitrogen fertiliser are not taken into acoount, hence nitrous oxide emissions are not included. To obtain carbon emissions from nitrogen fertiliser production ($N_{fert}$ $CO_2$ eq), the applied synthetic nitrogen fertiliser ($N_{synfert}$) [kg/ha] is converted using a conversion factor of 5.62 $CO_2$ eq/kg fertiliser nitrogen.[26]

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[21] Due to the focus on conventional crop production systems, only agri-environmental-climate measures from the Rural Development Programme are included.

[22] Landesbetrieb Landwirtschaft Hessen (LLH) 2018. Berechnung der Preiswürdigkeit von Einzelfuttermitteln für Schweine nach der Austauschmethode Löhr. Excel-based calculation tool. Landesbetrieb Landwirtschaft Hessen. Available at: https://www.proteinmarkt.de/aktuelles/schweine/rationsberechnung

[23] Corresponding to the fact that low market value of legumes is particularly an issue for legumes other than soybean, the price variations were not assumed for soybean.

[24] Also no price variations for legumes harvested for forage were assumed as in these cases on-farm use is primarily given.

[25] Retrieved from Eurostat – Prices for toasted extracted soyabean meal and fodder wheat from 2018 from the respective countries. https://ec.europa.eu/eurostat/databrowser/view/APRI_AP_INA__custom_152018/default/table?lang=en.

[26] Kool, A., Marinussen, M., Blonk, H. 2012. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization. GHG Emissions of N, P and K fertiliser production. Gouda, the Netherlands: Blonk Consultants.

$N_{fert}\ CO_2\ eq = N_{synfert} * 5.62$

Two levels of the $CO_2$-tax are assumed – one carbon tax of 150 €/t $CO_{2\ eq}$ (A) and one with 50 €/t $CO_{2\ eq}$ (B). These are additionally to total variable costs deducted from the revenue:

(A) $GM = R_C - C_{VAR} - N_{fert}\ CO_2\ eq * 0.15$

(B) $GM = R_C - C_{VAR} - N_{fert}\ CO_2\ eq * 0.05$

*Production related indicators*

1. Protein output

To obtain the protein output ($Y_{Prot}$) [kg/ha], dry matter yields ($Y_{DM}$) [t/ha] are converted into protein yields using standard conversion factors for crude protein (CP) [% DM] from feedtables.[27] [28]

$Y_{Prot} = Y_{DM} * CP * 1000$

Default conversion factors for dry matter fraction are assumed.[29]

2. Energy output

The energy output ($Y_{Ener}$) [GJ/ha] is also calculated based on dry matter yield and conversion factors on gross energy (GE) [GJ/t DM].[30] [31]

$Y_{Ener} = Y_{DM} * GE$

3. Yield stability

Based on yield data from either field trials or regional statistics, yield stability is calculated with the coefficient of variation (CV) [%]:

$CV = \frac{\sigma}{\mu}$

With $\sigma$ as the standard deviation and $\mu$ as the mean.

[27] https://www.feedipedia.org/
[28] https://www.feedtables.com/
[29] IPCC 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Switzerland: IPCC.
[30] https://www.feedipedia.org/
[31] https://www.feedtables.com/

*Environmental and climate indicators*

1. Nitrogen fertiliser

Nitrogen fertiliser use is calculated with nitrogen inputs from organic and mineral nitrogen fertilisers:

$$N_{fert} = N_{synfert} + N_{orgfert}$$

$N_{fert}$ is the nitrogen fertiliser use in kg/ha. $N_{orgfert}$ is the total nitrogen in organic fertilisers in kg/ha and $N_{synfert}$ is the total nitrogen in mineral nitrogen fertilisers in kg/ha.

2. Nitrate leaching

Based on a modelling approach[32] the nitrate-N leaching potential was assessed by calculating nitrate-N as a function of the soil leaching probability ($L_P$) and nitrogen surplus ($N_{sur}$):

$$N_{lea} = N_{sur} * L_P$$

$N_{lea}$ is the nitrate-N leaching potential during winter in kg/ha, $N_{sur}$ is the N surplus at the end of the growing season in kg/ha as defined below and $L_P$ is the N leaching probability during winter [with a value between 0 and 1], calculated with mean winter precipitation (MWP) [mm] divided by the water holding capacity at rooting depth (WHC) [mm]:[33] [34]

$$L_P = MWP/WHC$$

Nitrogen surplus ($N_{sur}$) [kg/ha] is a sum of nitrogen fertiliser [kg/ha][35] and nitrogen mineralisation ($N_{min}$) [kg/ha] deducted by the nitrogen derived from soil ($N_{dfs}$) [kg/ha]:

$$N_{sur} = N_{fert} + N_{min} - N_{dfs}$$

$N_{sur}$ is the N surplus at the end of the growing season in kg/ha, $N_{fert}$ is the sum of total N in mineral nitrogen fertilisers and plant-available N in organic fertiliser in kg/ha, $N_{min}$ is the nitrogen mineralisation. $N_{min}$ is assessed as a function of total organic nitrogen content in the ploughing zone ($N_{org}$) [kg/ha] and mean annual soil nitrogen mineralisation rate ($R_{mina}$) [%] modified by pre-crop specific nitrogen supply level ($R_{minNL}$) and a crop-specific mineralisation coefficient ($R_{minC}$). $N_{min}$ is calculated as:

$$N_{min} = N_{org} * R_{mina} * R_{minNL} * R_{minC}$$

$R_{minNL}$ is the coefficient of the preceding crop specific residual nitrogen level.[36] The crop-specific mineralisation coefficient ($R_{minC}$) modifies the nitrogen mineralisation depending on the crop and associated production activities.[37]

[32] Reckling, M., et al. 2016. A cropping system assessment framework—evaluating effects of introducing legumes into crop rotations. Eur. J. Agron. 76, 186–197. doi: 10.1016/j.eja.2015.11.005.
[33] In terms of the considered perennial crops alfalfa, grass-clover and grass a crop-specific leaching coefficient of 0.2 was multiplied with $L_P$.
[34] $L_P$ values > 1 were set to 1.
[35] Nitrogen fertiliser is calculated as in 1. Nitrogen fertiliser, with the modification to only include plant-available N from organic fertilisers.
[36] Three pre-crop categories are differentiated: (i) cereals and maize; (ii) grain legumes, rapeseed and grass; (iii) forage legumes in pure stands and in mixtures with grass (> 30 % legumes).

The total organic nitrogen content in the ploughing zone ($N_{org}$) in kg/ha is calculated as follows:

$$N_{org} = R_{Corg} * R^{-1}_{CN} * BD * D_{AP} * 10^3$$

with $R_{Corg}$ as the content of organic carbon in topsoil [%], $R_{CN}$ as the C/N ratio, BD as the bulk density [g/cm$^3$] and $D_{Ap}$ as the depth of ploughing horizon [cm].

Nitrogen derived from soil ($N_{dfs}$) [kg/ha] is calculated according to:

$$N_{dfs} = N_{upt} – N_{fix}$$

with nitrogen uptake ($N_{upt}$) [kg/ha] as the nitrogen which is accumulated by the crop and nitrogen fixation ($N_{fix}$) [kg/ha] as the biological nitrogen fixation of grain and forage legumes.

The nitrogen fixation for sole cropped grain and forage legumes and cereal legume-mixtures is calculated as:

$$N_{fix} = Y * N_C * R_{NR} * R_{Nfix} * R_L$$

$N_{fix}$ is the biological nitrogen fixation in kg/ha with Y as the yield [converted from t/ha into kg/ha for $N_{fix}$], $N_C$ as the nitrogen content of the harvested grain dry matter [%], $R_{NR}$ as the crop specific ratio of nitrogen in grain yield to nitrogen in crop and root residues, $R_{Nfix}$ as the ratio of symbiotically fixed nitrogen to total nitrogen in the plant and $R_L$ as the legume portion in the dry matter yield in case of cereal-legume mixtures. $R_{Nfix}$ is dependent on the soil content of mineralised nitrogen from preceding crop residues in spring, and on inputs from organic, plant-available nitrogen in manure and mineral fertiliser. In the model it is assumed that $R_{Nfix}$ is a linear function of plant-available nitrogen in the soil ($N_{soil}$) as described by Reckling et al. 2014.[38]

The nitrogen fixation of legume-grass mixtures can be calculated for different percentages of legumes in the dry matter of the gross yield according to:

$$N_{fix} = (Y_{tot} * R_L * N_L * R_{Nres} * R_{LNfix} + Y_{tot} * (1 – R_{Lb}) N_G * R_{Gnfix}) * 10$$

with $Y_{tot}$ as the total dry matter yield without harvest losses at 5 cm cutting height [t/ha] (calculated as $Y_{tot} = Y^{-1} * R_{Hloss}$ where $R_{Hloss}$ is the ratio of harvest losses set to 0.65 for hay and 0.85 for silage crop). The legume portion in the dry matter yield is $R_L$, $N_L$ is the nitrogen content in legume dry matter [%], $R_{Nres}$ the ratio of nitrogen in legume yield to nitrogen in stubble and root residues, $R_{LNfix}$ the ratio of symbiotically fixed nitrogen to total nitrogen in legumes, $N_G$ is the nitrogen content in grass yield, and $R_{GNfix}$ is the ratio of fixed nitrogen transferred to grass ($R_{GNfix} = 0.25 * R_L$).

[37] Apart from maize silage, lupin, pea, faba bean (1.1), soybean, winter rape, sugar beet (1.2), grain maize (1.3), sunflower (1.4) and alfalfa and grass-clover (1.5), all crops have a coefficient of 1.0.
[38] Reckling, M., Schläfke, N., Hecker, J.-M., Bachinger, J., Zander, P., Bergkvist, G., Frankow-Lindberg, F., Båth, B., Pristeri, A., Monti, Toncea, I., Walker, R., Topp, C.F.A., Watson, C. 2014. Generation and evaluation of legume-supported crop rotations in five case study regions across Europe. Legume Futures Report 4.2.; www.legumefutures.de.

3. Nitrous oxide emissions

Nitrous oxide emissions are computed with the IPCC 2006 Tier 1 methodology, taking into account the refinements from 2019.[39] [40] Direct ($N_2O$ direct) and indirect emissions ($N_2O$ indirect) from the managed soils are considered:

$$N_2O = N_2O \text{ direct} + N_2O \text{ indirect}$$

Direct emissions include emissions from mineral and organic fertilisers as well as from crop residues:

$$N_2O \text{ direct} = ((F_{SN} + F_{ON} + F_{CR}) * EF_1) * (44/28)$$

with $F_{SN}$ as the annual amount of mineral fertiliser nitrogen applied to soils [kg N/year] and $F_{ON}$ as the annual amount of organic total nitrogen additions applied to soils [kg N/year] and $F_{CR}$ as the annual amount of nitrogen in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils [kg N/year]. Emission factors for wet climate are applied and dependent on the respective nitrogen inputs chosen.[41]

The multiplication with 44/28 transforms the result into from $N_2O$-N into $N_2O$ emissions. Indirect emissions occur through two indirect pathways, nitrogen volatilization ($N_2O_{ATD}$) as well as leaching and runoff ($N_2O_L$):

$$N_2O \text{ indirect} = N_2O_{ATD} + N_2O_L$$

with $N_2O_{ATD}$ [kg/ha] as the nitrous oxide emissions from atmospheric deposition of nitrogen volatilized from managed soils, calculated according to:

$$N_2O_{ATD} = (F_{SN} * Frac_{GASF} + F_{ON} * Frac_{GASM}) * EF_4 * (44/28)$$

with $F_{SN}$ and $F_{ON}$ as described above and $Frac_{GASF}$ as the volatilization factor from mineral fertiliser depending on the form in which nitrogen is given in the product[42] and $Frac_{GASM}$ as the volatilization factor from organic fertiliser which is 0.21. Emission factor 4 for wet climate is equivalent to 0.014.

Emissions from leaching ($N_{lea}$) were included with the results from "2. Nitrate leaching" (see above) converted with the emission factor 5 which is equivalent to 0.011:

$$N_2O_L = N_{lea} * EF\ 5 * (44/28)$$

[39] IPCC 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Switzerland: IPCC.

[40] According to the guidelines $N_2O$ emissions from biological N-fixation is assumed to be zero.

[41] The emission factor for mineral fertiliser is 0.016 and for all other nitrogen inputs (organic amendments, animal manures or nitrogen in crop residues) 0.006.

[42] Factors applied are the following: Urea 0.15, ammonium-based 0.08, nitrate-based 0.01 and ammonium-nitrate based 0.05.

4. Crop diversity

Crop diversity is computed with the Shannon diversity index.[43] For the index 3 species groups (S= 3) are taken as a basis - cereal, leaf and legume crops. Therefore the maximum value of diversity ($H_{max}$) is by definition the logarithm of 3:

$H_{max} = \ln S$

$H_{max} = \ln 3 \approx 1.099$

The respective diversity index for each rotation ($H_S$) are calculated by taking the negative sum of the multiplied proportion of crops belonging to each species ($p_i$) with the logarithm of this proportion:

$$H_S = -\sum_{i=1}^{S} p_i * \ln p_i \qquad \text{with} \qquad p_i = \frac{n_i}{N}$$

with $n_i$ as the number of crops within one species and N as the total number of crops within one rotation.

## Results

### Assessment of legume-supported cropping systems across all regions[44]

Considering the results of arable cropping systems without legumes and alternative legume-supported cropping systems within the economic impact area, we show that there was no significant or consistent difference between the systems' standard gross margins. Only a minimally lower GM (3% less) was given for rotations with legumes. When modifying the standard GM using the legume feed value as a price or by including subsidies, or levying a carbon tax of 150 €/t $CO_{2\ eq}$, the economic performance of the cropping systems with legumes increases, leading to 5%, 8% and 17% higher GMs, respectively. A lower carbon tax of 50 €/t $CO_{2\ eq}$ results in no significant difference between the GM of cropping systems with and without legumes.

For environmental and resource impacts, the cropping systems with legumes had 26% less nitrogen fertiliser use, 21% less nitrous oxide emissions and no significant effect on nitrate leaching. The average crop diversity index was raised by 44% when including legumes to the cropping system, with an index value of 0.31 of the non-legume systems compared to 0.79 for the legume-supported systems.

The production related indicators showed that there was no difference in the yield stability between the systems. Concerning the protein output, legume-supported systems had on average 13% higher protein yields. However, the energy output was 10% lower in the cropping systems with legumes.

[43] Shannon, C. E., 1948. A mathematical theory of communication. The Bell System Technical Journal, 27, 379–423 and 623–656. doi: 10.1002/j.1538-7305.1948.tb01338.x.
[44] An overview on all results is provided in Annex IV.

For forgage croping systems, the average effects were stronger for some indicators than for arable systems. The standard GM was 47% higher in the legume-supported systems. This increased to 51% higher GM when taking the feed value into account, 152% higher GM with a carbon tax of 150 €/t $CO_{2\ eq}$ and 68% higher with a carbon tax of 50 €/t $CO_{2eq}$.

For environment- and climate-related impacts, there was 45% less nitrogen fertiliser use, 26% less nitrous oxide emission and 11% higher nitrate leaching. Crop diversity was similar in the compared cropping systems with and without legumes, both having an index value of 0.62. Concerning the area of production, the yield stability could only be calculated for the example in Brandenburg, but here the results were similar for non-legume and legume-supported systems. In terms of protein and energy yield, cropping systems with legumes received 5% higher protein output, but 9% less energy output.

**Assessment of legume-supported arable cropping systems for specific regions**

*Central-eastern Europe*

Considering the broader region of central-eastern Europe represented by four countries – Bulgaria, Romania, Serbia and Ukraine – seven different case study regions were included in the analysis. In five of the examples the legume-supported rotations included soybean.

The average economic performance of cropping systems with legumes in central-eastern Europe was slightly lower than from the non-legume systems with 9% lower standard GMs. Including subsidies or a carbon tax of 150 €/t $CO_{2\ eq}$ eliminated this difference and led to equivalent results. GM modifications with the feed value as legume price and the lower carbon tax resulted in 4% and 7% lower GMs, respectively. However, in the specific regions there were also more beneficial economic performances of legume-supported rotations: in Serbia, the north-eastern Romania (RO 21) and Ukraine the cropping systems including soybean resulted in 70%, 12% and 5% higher standard GM, respectively. The considerably higher standard GM in Serbia was due to higher yields in winter wheat and maize when soybean was introduced to the rotation. Also reduced costs of crop protection for maize following soybean as well as the high profitability of soybean cultivation itself improved the GM. Lower economic returns were especially found in regions without soybean, but pea or common bean. Low prices as well as yields for pea and common bean in the regional examples in Bulgaria caused low or even negative GMs for the grain legumes which impacted the rotational GM. The inclusion of the VCS which was given in Bulgaria as well as Romania showed in all compared systems effects, with reducing the deficit from the legume-supported rotation to the respective non-legume rotation (BG 31, BG 33) or turning the economic disadvantage into an advantage (BG 32, RO 11) or strengthening the already given monetary benefit (RO 21).

Considering the impact area of environment and climate the averages for the regions in central-eastern Europe showed 24% less nitrogen fertiliser use and 16% less nitrous oxide emissions. The greatest effects for both indicators were found for the soybean rotation in Severen Tsentralen in Bulgaria (BG 32) in which fertilisation was reduced by 54% and the nitrous oxide emissions by 45%. These reductions were mainly caused by the fact that no nitrogen fertiliser was applied on soybean, the reduced fertilisation of winter wheat in the legume-supported rotation as well as the presence of the highly fertilised maize in the non-legume rotation. The north-eastern region in Romania (RO 21) was exceptional for the indicator of fertilisation, as the amount of nitrogen applied was in both cropping systems similar whereas in all other regions a reduction of nitrogen application was given. Also the nitrous oxide emissions differed in the case of north-eastern Romania, with being the only example in which the legume-supported rotation caused higher nitrous oxide emissions than the non-legume rotation (8% higher emissions). The main contributory factors were the higher yields in the cropping system with legumes that caused higher direct nitrous oxide emissions from crop residues, but also higher indirect nitrous oxide emissions from nitrate leaching. The nitrate leaching on average across all central-eastern European regions was 7% higher in the cropping systems with legumes. Considering the single regions, however, it was shown that only in three of them (BG 33, RO 21, Kyiv oblast) the legume-supported rotations had higher nitrate leaching. In all three cases there were nitrogen fertilisers applied to the legume crops and the yield level were low (2 t/ha for common bean) or moderate (3 t/ha for soybean in Ukraine and 2.8 t/ha for soybean in Romania). Moreover, in the Ukrainian as well as the Romanian example the nitrogen fertilisation of the crops following the legumes were not reduced. In terms of crop diversity, the average index value of central-eastern Europe indicated with 0.85 for the legume-supported crop rotations more diversified systems than for the non-legume rotations with 0.46. This on average 35% higher crop diversity was in all regions in more or less extreme differences present, only in the rotations in the example from north-eastern Romania the diversity index was similar. This was due to the fact that the difference in the sequences was only soybean replacing another break-crop - sunflower. The highest diversity gain was given in Serbia where a two-year maize–winter wheat rotation was expanded with the introduction of soybean.

Production related indicators showed on the overall average neutral, positive or negative results for the cropping systems with legumes: the yield stability was on the same level, the protein output was 14% higher and the energy output was 12% lower. Considering the single regions the similar level of yield stability in cropping systems with and without legumes were given in all cases, despite in the Bulgarian examples from Severen Tsentralen (BG 32) and Severoiztochen (BG 33) in which yield stability was 7 and 8 percentage points lower, respectively. In both examples the increased yield instability was caused by the grain legumes – soybean and common bean – which had considerably higher coefficient of variations. Concerning the protein and energy output, the strongest effects were found in the Serbian example which again can be traced back to the higher yielding maize and winter wheat in the legume-supported alternative, and in terms of the protein output also to the high protein yield of soybean. The – compared to the reference systems - lowest energy outputs were given in regions (BG 32, BG 33, RO 11) where the grain legumes had particular low yields and no or only small yield effects on the following crops.

*Central-western Europe*

Two case study regions in Austria and four case study regions in Germany were provided from project partners interested in a range of grain legumes. Besides soybean including cropping systems in Niederösterreich (AT 12), the Burgenland (AT 11), southern (DE 13) and north-eastern Germany (DE 40), pea, faba bean as well as lupin were integrated in regional crop rotations (DE 11, DE 40, DE 73). On average across these regions, cropping systems with legumes had 8% lower standard GMs. When including a carbon tax of 50 €/t $CO_{2\ eq}$ this disadvantage was slightly decreased to 6%. Levying a higher carbon tax of 150 €/t $CO_{2\ eq}$ removed the disadvantage. Exchanging the legume market price with the actual feed value had the same effect and no difference between cropping systems with and without legumes was found. Adding the subsidies to the GM calculation, resulted in 5% higher GMs for the legume-supported rotations.

Considering the single case studies, an economic benefit of the soybean including rotations in both Austrian regions was found. The advantages were even raised when including the carbon taxes. In the German case studies no cropping system with legume had a higher standard GM than the reference system, however, the soybean including systems from Brandenburg (DE 40) and the Markgräflerland (DE 13) had only by 4%, 8% and 13% reduced GMs. When including the payments for crop diversification from the FAKT program in Baden-Württemberg these deficits were offset and the systems with soybean were more profitable with 2% and 10% higher GMs.[45] The greatest reduction of the standard GM with 35% was found for a faba bean supported rotation in Hohenlohekreis (DE 11). This was caused by the substitution of one profitable year of maize with low yielding faba bean that additionally achieved only low market prices. Pea-supported rotations were provided from case study regions in Nordhessen (DE 73), Brandenburg (DE 40) and also Hohenlohekreis (DE 11). In all regions the standard GMs were reduced by 14%-24%, mainly because of low yields and prices for pea. The reference cropping system without legumes in Brandenburg performed also better than the lupin alternative which illustrates reasons for the decreasing farmers' interest in a formerly relevant crop and declining lupin shares in this area. The GMs clearly increased when using the feed value as legume prices and even led to an equivalent economic performance of pea-supported rotation and reference system in Hohenlohekreis (DE 11). Moreover, when not the feed value was taken into account, but the subsidies for crop diversification were included, it had also strong effects on the economic performance of pea and faba-bean rotations, resulting in up to 20% and 23% higher GMs in Nordhessen (DE 73) and Hohenlohekreis (DE 11), respectively.[46]

In the impact area of environment and climate the average from central-western Europe showed 26% less nitrogen fertiliser use, 20% less nitrous oxide emissions, no increase in nitrate leaching and an increase by 39% in crop diversity (0.45 vs. 0.88) for cropping systems with legumes. All legume-supported rotations used less fertiliser, varying between a reduction of 16-41%. The greatest effects were found in the Burgenland (AT 11) where the diversification with soybean of the three-year rotation with maize and winter wheat, allowed considerable nitrogen savings in the year of soybean itself as well as in winter wheat following soybean. These lower nitrogen inputs were also reflected in the nitrous oxide emissions. With 31% less nitrous oxide emissions the cropping system with soybean in the Burgenland (AT 11) also had the greatest difference to its reference system. The smallest effect was found in Niederösterreich (AT 12) with only 6% lower emissions. This was due to the fact that management practices were not modified in the legume-supported rotation. Furthermore, soybean replaced sunflower which was receiving comparatively low nitrogen inputs as well as leaving less crop residues behind, resulting in modest nitrous oxide emissions. The same aspects caused a higher rotational

[45] The requirements that have to be met for crop diversification are to cultivate a minimum of five crops and at least 10% legumes. As these requirements can be met on the area of the whole farm, the additional assumption was made that a fifth crop is cultivated additionally to the four crops in the rotation.
[46] The additional assumption on a fifth crop were also made in these examples.

nitrate leaching of the soybean rotation. In most of the other case study regions, the legume-supported rotations were not differing in the nitrate leaching - as in both examples from the Markgräflerland (DE 13) and the Burgenland (AT 11) – or even had lower nitrate leaching with a reduction between 12%-18% (DE 11, DE 40, DE 73). A considerably higher leaching was found in the faba bean rotation from Hohenlohekreis (DE 11), because higher leaching was calculated for faba bean than maize which it replaced. The moderate fertilisation of the high-yielding maize compared to the low-yielding faba bean resulted in a higher nitrogen surplus for the latter. Considering the crop diversity, all legume-supported crop rotations except for the example from Niederösterreich (AT 12) were more diverse, increasing the diversity between 35%-58%. The greatest effect were found in examples in which legumes were integrated in purely cereal-based rotations. No effect was found when soybean replaced another break crop.

Yield stability was on average across the regions in Germany and Austria on the same level for cropping systems with and without legumes. Protein output was 10% higher and energy output 10% lower for legume-supported rotations. The single examples showed that yield stability was decreased in two examples – in the lupin including rotation from Brandenburg (DE 40) and the soybean-supported rotation in the Burgenland (AT 11). In both cases issues with yield stability were found in the legume crops. The greatest effects in terms of the protein output were given in both Austrian examples, with 24% and 39% higher protein yields for the soybean rotations. The driver was here the moderate and high yield level of soybean in Niederösterreich (AT 12) and the Burgenland (AT 11), respectively. The case study in Niederösterreich was also the only one with a similar energy output of the cropping systems with and without legumes, because soybean was replacing sunflower and similar yield levels of the crops were given. In the other regions the energy output was 5%-19% lower, with highest differences in examples in which high-yielding crops as maize were substituted with the grain legumes.

*North-western Europe*

Within north-western Europe the case study regions of eastern Scotland and southern Ireland combined with eastern and Midland Ireland were considered. In both countries faba bean is a relevant grain legume that was included in the cropping systems. In Scotland pea was also included in the data set.[47]

The average results from both regions showed that the standard GM for cropping systems with and without legumes was similar. With the introduction of a carbon tax of 50 €/t $CO_{2\ eq}$ the GM was still on the same level. Rising the tax to 150 €/t $CO_{2\ eq}$ caused 8% higher GMs for the legume-supported rotations. Considering the single examples, the equal economic performance of cropping systems with and without legumes was present in eastern Scotland. The main reasons were the comparably high yield and market value of pea and faba bean as well as their pre-crop effect on the following cereals causing higher yields and reduced fertilisation costs. In the Irish example, that focused on winter crops, a 7% lower standard GM was given. This was caused by changing the six-year rotation to a five-year rotation in which faba bean was introduced and one year of highly profitable winter barley and one year of winter oilseed rape were removed. In the Irish

[47] The Scottish examples should not be understood as representative for the United Kingdom, as there can be differences between UK values and those specifically for Scotland.

example that focused on spring crops, however, a 7% higher standard GM could be achieved. The major reason was a significantly higher revenue – due to higher prices - of spring oats after faba bean than after spring malt barley, as given in the non-legume rotation. By inserting a break-crop before spring oat, it is possible to market oats as gluten free which attracts a higher price. In all examples the substitution of the market legume prices with the feed value led to more beneficial GMs for the cropping systems with legumes. The strongest effects were given for the Irish examples in which the difference between the calculated feed value and the declared market price of faba bean was very high.[48] Moreover, the inclusion of the payments from the protein aid scheme in Ireland caused also more profitable economic returns from the rotations with faba bean, leading to 4% and 24% higher GMs in the considered examples.

In the impact area of environment and climate all comparisons showed positive results for the legume-supported systems. On average across north-western Europe, nitrogen fertiliser use of cropping systems with legumes was 25% lower, nitrous oxide emissions were 20% lower, nitrate leaching was 21% lower and crop diversity was 37% higher with an index value of 0.73 compared to 0.32. The strongest effects for the nitrogen related indicators were found for the Scottish examples in which the nitrogen fertiliser dose to cereal crops following pea or faba bean was considerably reduced. The highest gain in crop diversity was given in the Irish example focused on spring crops: through replacing spring malt barley with faba bean the cereal monoculture was diversified by 46%, increasing the crop diversity index from 0.0 to 0.50.

Considering the impact area of production it was apparent that no difference in yield stability was found in any of the compared cropping systems. All rotations with legumes achieved higher protein output, having 10%-22% higher protein yields. The major contributing factor was the high yield level of pea and faba bean in the considered systems. The average energy output from north-western Europe was similar in cropping systems with and without legumes. Focusing on the single regions, only minimally lower energy yields in two examples (4%-6% less) could be noticed.

*Southern Europe*

One single case study from Friuli-Venezia Giulia in northern Italy represents the region of southern Europe. Soybean is cultivated on more than 29% of the agricultural area in Friuli-Venezia Giulia and generally the agricultural area is mostly used for arable crops and pastures.[49] The provided cropping systems allowed a comparison between a maize-monoculture and a two-year soybean-maize rotation.

The inclusion of soybean had a considerable effect on the yield level of maize, causing an extreme economic advantage. The standard GM of the legume-supported rotation was 93% higher. The effect was even greater when including the VCS (Colture proteiche nel Nord Italia (soia)) that is paid for soybean in northern Italy or the carbon tax. Both level of carbon taxes had a substantial effect as the fertiliser use was reduced by 54% in the rotation with soybean which was directly reflected in the GMs including the carbon tax.

[48] More details on the calculated feed value and specific differences between market prices and feed value are discussed in Deliverable Report 4.2.
[49] European Commission 2020. Factsheet on 2014-2020 Rural Development Programme for Friuli Venezia Giulia.

The significantly lower fertiliser use was also the major contributory factor for the by 63% reduced nitrous oxide emissions and by 30% reduced nitrate leaching. Due to the monoculture cropping in the reference rotation, the diversity index was 0.0 compared to 0.69, allowing an increase by 63%.

The production related indicators showed a small decrease in yield stability with 4 percentage points for the rotation with legume, because of a lower yield stability of soybean. The protein output was 35% higher and the energy output 20% lower in the legume-supported system. A high protein yield of soybean was given due to the 4 t/ha exceeding yield. However, as the maize yield was about three times as high, the energy output of soybean was only half of one year of maize, causing the reduction in the rotational energy output.

*Differences found in soybean, pea and faba bean supported cropping systems*

The results from the broader regions already indicated differences between soybean, pea and faba bean supported cropping systems. Considering the summarized results of these three grain legumes, several distinctive findings were observed.
On average across central-eastern, -western and southern Europe, arable cropping systems including soybean had 19% higher standard GMs than the systems without legumes. Comparing the average standard GMs from all pea-supported rotations in central-eastern, -western and north-western Europe which had 16% lower GMs than their reference systems. Rotations with faba bean were summarized from north-western Europe and one single example in Germany (DE 11). The average standard GM was 9% lower for the faba bean rotations than from the reference systems, however the reduction was mainly driven by the unprofitable faba bean rotation in Hohenlohekreis in Germany (DE 11). The more beneficial performance of soybean including rotations was mainly due to higher soybean prices.[50] This high relevance of prices became also evident when exchanging the pea and faba bean market prices with their calculated feed value. With the modified GM the average from the pea-supported rotations showed no significant decrease anymore and the faba bean rotations had on average a 12% higher GMs than their reference systems. The inclusion of subsidies had a similar effect for the pea- and faba bean-supported rotations removing the economic disadvantages compared to the non-legume rotations. In the soybean involving case studies the economic benefits were increased to on average 27% higher GMs.

Considering the environmental effects, the nitrogen savings in soybean, pea and faba bean supported rotations compared to their reference systems were on the same level, ranging between 26%-28% lower uses for the legume rotations. The same was found for nitrous oxide emissions, which were between 19%-22% lower in the cropping systems with soybean, pea and faba bean. In terms of the nitrate leaching the soybean supported rotations were on average on a similar level as their reference cropping systems. However, the pea-supported rotations had on average 16% lower leaching results. This difference was caused by the fact that starter nitrogen was applied in higher doses in some soybean examples and pea involving cropping systems were rather adapted in their fertilisation practices after the introduction of the legume. Moreover, pea were in all

[50] Differences and consequences of prices of soybean, pea and faba bean are discussed more in detail in Deliverable Report 4.2.

examples added as an additional crop to the rotations whereas soybean were in several cases substituting other break-crops with low leaching values. The faba bean rotations were, concerning the leaching results, on a slightly higher level to their reference systems, but this disadvantage was mainly caused by the very unfavorable German example.

Differences in the yield stability were only found for the soybean rotations in which three case study regions showed a minimally decreased yield stability by 4, 6 and 7 percentage points. The protein output was on average for all soybean rotations 23% higher, for the pea including rotations 4% and for the faba bean rotations 13% higher. These results reflected the actual protein contents of the crops with highest value for soybean, followed by faba bean and the lowest shares for pea. The energy output was mostly on the same level with 10% lower energy output for the soybean and pea supported rotations and 7% less energy yield for the faba bean including systems compared to the systems without legumes. The latter had a smaller reduction compared to their reference system mostly due to the high yield level of faba bean in north-western Europe.

**Assessment of legume-supported forage cropping systems**

Forage cropping systems with and without legumes were covered in only two case study regions. In Brandenburg a five-year rotation with winter wheat, winter rye and silage maize was compared with an alternative including alfalfa. In southern Scotland six alternative cropping systems with grass-clover and alfalfa as well as pea and faba bean were compared with a grass-spring barley rotation.

In the impact area of environment and climate the cropping systems with legumes had the largest effect in the indicator of nitrogen fertiliser use for which they reduced the input by 23-87%. Nitrous oxide emissions were also found to be lower in all legume-supported alternatives, with a reduction between 12-61%. The greatest effect for those two indicators were given in one of the Scottish examples in which pure grass stands of the non-legume rotation were substituted with unfertilised alfalfa. The second largest effects were found in the example from Brandenburg in which silage maize was also replaced with unfertilised alfalfa. For both examples the nitrate leaching was also reduced, in Scotland by 36% and in Brandenburg even greater by 63%. However, considering the other alternatives with legumes from Scotland, it was noticed that the nitrate leaching was increased by 22-51% compared to the four-year rotation based on perennial grass and spring barley. The major contributory factor to this increase was the inclusion of winter wheat in these systems. Winter wheat received higher doses of nitrogen fertilisation resulting in higher nitrate leaching. This effect was strongest in the rotation with winter wheat following spring barley, as in this example the highest fertilisation was applied; in the other legume-supported alternatives the fertilisation could be reduced due to the pre-crop effect from either grain or forage legumes. There was no considerable difference found in the nitrate leaching of grass and grass-clover. In terms of the crop diversity a similar index of 0.67 was found in the cropping systems with and without legumes in Brandenburg. The Scottish cropping systems with legumes were slightly more diverse (0.62) than the non-legume system (0.56). The 5% higher crop diversity was given mostly due to an increased total rotation length.

The economic performance of the cropping system with alfalfa in Brandenburg was lower than the compared non-legume rotation. The substitution of silage maize with alfalfa resulted in a 14% reduction of the standard GM. The reason were higher revenues due to higher yields from silage maize compared to alfalfa. Even though silage maize came along with considerably higher production costs than alfalfa, because of higher costs in fertilisation and plant protection measures, the saving in variable costs could not compensate the lower revenues. Additionally, the yield benefit of wheat after alfalfa could not lead to an economic benefit in terms of the rotational GM. With the introduction of a carbon tax the GM deficit of the legume-supported rotation could be decreased due to the considerably lower usage of nitrogen fertiliser, but there was still a GM deficit of 5% or 12%, depending on the height of the carbon tax.

Five of the six Scottish rotations with legumes achieved significantly higher economic returns than the non-legume rotation. The standard GM was between 64%-133% higher. This was caused by lower variable costs in grass-clover than in pure grass stands due to reduced fertilisation and yield benefits in cereals grown after grass-clover as well as after the grain legumes, included in three of the grass-clover rotations. Additionally, fertilisation costs of cereals after legumes were also slightly lower due to implemented savings in nitrogen fertilisation. Substituting grass with alfalfa, however, resulted in an almost negative GM, leading to a 96% lower standard GM than from the non-legume rotation. This was caused by the highly unprofitable GM of the first year of alfalfa due to reduced yields during the establishment of the stand and at the same time higher variable costs as a result of the costs of seeds and establishment. Yield benefits and reduced fertilisation costs of spring barley after alfalfa compared to the spring barley after grass could not outbalance the economic disadvantage. Modifying the standard GM with the inclusion of a carbon tax resulted in even higher advantages of the grass-clover rotations compared to the grass-rotation, however the alfalfa-rotation could not benefit in the comparison due to the initially very low economic return.

The production related indicators showed on average only small effects in the comparisons. Yield stability could only be assessed for the German systems, in which no difference could be recognized. The protein output was higher in two legume-supported rotations. The example from Brandenburg showed an increase of 55% in the protein yield due to the considerably higher protein content of alfalfa compared to silage maize. Besides, the pre-crop effect from alfalfa on winter wheat resulted in a higher winter wheat yield which also increased the protein output. The four-year rotation with grass-clover and winter wheat from Scotland achieved a 10% higher protein output than the grass-spring barley rotation, because of higher protein contents of grass-clover compared to pure grass and winter wheat compared to spring barley. The higher share of cereals in the other Scottish legume-supported rotations were one reason for lower protein outputs in these examples. The inclusion of pea and faba bean in these examples could also not support higher rotational protein yields, as compared to grass the protein output of pea and faba bean were also still lower due to lower yield levels. In terms of the alfalfa rotation, the already above mentioned lower yield levels, particularly in the establishing year caused the 13% lower protein output compared to the non-legume rotation. This yield deficit was also the reason for the lowest energy output within the Scottish examples - the alfalfa-rotation had a 29% lower energy output than the grass-rotation. Only the four-year grass-clover-winter wheat rotation had a 5% higher energy output than the non-legume rotation which was due to the replacement of spring barley with the higher yielding winter wheat. In Brandenburg the alfalfa-rotation had a 13% lower energy output than the non-legume rotation which was mostly because of the higher yield level and energy content of silage maize.

## Discussion

Diversification of cropping systems with legumes were described as beneficial due to the positive rotational effects of legumes that can particularly improve the environmental performance of farming systems.[51] The main resource benefit that fosters the positive environmental performance is the reduced nitrogen fertilisation in legume-supported cropping systems that is enabled through the biological nitrogen fixation (BNF) of legumes.[52] The assessment of the data set from Legumes Translated showed the reduction of nitrogen fertilisation of the legume-supported cropping system in 16 out of the 17 case study regions. The savings varied between 5-54% in arable cropping systems and 23-87% in forage cropping systems.

The quantity of nitrogen fixed depends, next to environmental factors, also on the legume species, with the highest amounts fixed from perennial forage legumes due to high biomass production and longer growth periods.[53] This was also displayed in the magnitude of the realized savings, since the greatest reductions were found in the 3-year alfalfa-supported cropping systems. Both the Scottish (UKM 9) as well as the example from Brandenburg (DE 40) showed extremely high fertiliser savings of 87% and 72%, respectively. Three years of unfertilised alfalfa had a considerable impact on the rotational nitrogen inputs, especially as they replaced highly fertilised grass or silage maize which increased the effect further and showed the significance of the reference crop in the compared cropping system.

The absence of nitrogen fertiliser in the year of the legume crop was also the main contributor to the total fertiliser savings over the rotations. However, several grain legumes received some "starter" nitrogen fertiliser and some of those exceeded the recommended amount. Under specific conditions, agronomists advise some nitrogen fertiliser to facilitate crop establishment while the symbiotic relationship with soil bacteria for nitrogen fixation is initiated.[49]

Next to savings of fertiliser in the year of the legume, the need of nitrogen from the following crop in the rotation is also reduced as organically bound nitrogen is left behind with the plant residues of the legume which is then available for the following crop.[54] The actual reductions depend on region-specific growing conditions and the trade-off that is

[51] Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., Alves, B.J.R., Morrison, M.J. 2011. Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. Agronomy for Sustainable Development 32, 329–364. doi:10.1007/s13593-011-0056-7.
[52] Watson, C., Reckling, M., Preissel, S., Bachinger, J., Bergkvist, G., Kuhlman, T., Lindström, K., Nemecek, T., Topp, C., Vanhatalo, A., Zander, Z., Murphy-Bokern, D., Stoddard, F. 2017. Grain legume production and use in European agricultural systems. Adv. Agron. 144, 235–303.doi: 10.1016/bs.agron.2017.03.003.
[53] Carlsson, G., Huss-Danell, K. 2003. Nitrogen fixation in perennial forage legumes in the field. *Plant and Soil, 253*(2), 353-372. doi:10.1023/A:1024847017371.
[54] Bues A., Preissel, S., Reckling, M., Zander, P., Kuhlmann, T., Topp, K., Watson, C., Lindström, K., Stoddard, F.L., Murphy-Bokern, D. 2013. The environmental role of protein crops in the new common agricultural policy, in: Agriculture and rural development. European Parliament, Brussels; http://edepot.wur.nl/262633.

made between securing maximum yields and maximizing fertiliser savings.[55] If nitrogen fertilisation is significantly reduced in the subsequent crop, the yield benefit is smaller, but if nitrogen fertilisation is kept at the same level as without legumes, the yield benefit can be raised to the highest level.[52] Consequently the ratio of fertiliser prices to product prices determines the appreciation of the biological nitrogen fixation and rising fertiliser costs could support a higher valuation than it is currently the case, since in real-life farming practices application rates are often not adjusted.[56]

This nitrogen effect is one part of the pre-crop effect of legumes. The other part is the so called break-crop effect, which impacts agronomic parameters such as soil, pests, weeds or diseases and therefore also the management requirements and yields. How the pre-crop effects are exploited in cropping systems and what actual effects they have, depends on several factors as management decision, crop species, regional conditions (climate and soil parameters) or design of cropping systems. The choice of the reference cropping systems is also relevant when quantfying these effects. Therefore, the quantification of the pre-crop effect is complex and site-dependent, which was also the situation in the case study regions. Next to yield benefits and nitrogen savings, adjustments of pesticides and tillage practices were applied in several legume-supported cropping systems, but also no yield effects and management adoptions were reported. When no effects were reported, this indicates either very favorable site conditions in which pre-crop effects are less observable or that systems were already diversified (largest effects are visible when cereal-dominated rotations are diversified with legumes), or that there is a lack of information and knowledge on the potential for optimizing management decisions to exploit the pre-crop benefits of legumes.

The variable extents of nitrogen reductions were also reflected in the nitrous oxide emissions. This is due to the strong correlation of nitrogen fertilisation and emissions of nitrous oxide.[57] Largest effects in forage cropping systems were found in the Scottish alfalfa-supported-rotation with emission reductions of 61%. Arable cropping systems including soybean allowed the highest reductions in Italy (ITH 4) and Bulgaria (BG 32) with 45% and 63%, respectively. In both cases the nitrogen fertiliser savings were highest among the arable cropping systems. Similar or slightly increased nitrous oxide emissions from cropping systems with legumes were shown in Severoiztochen (BG 33) and north-eastern Romania (RO 21) were only minimal or no differences in the rotational nitrogen input were reported.

The direct relation between nitrogen fertilisation and nitrous oxide emissions is also reflected within the applied methodological approach of the IPCC 2006 Tier 1 methodology (including the refinements from 2019). For modelling the direct emissions from organic and inorganic nitrogen fertilisers, it was assumed that 1.6% were released as emissions (IPCC 2019).[58] This emission factor (EF) was recently adjusted from 1% to

[55] Preissel, S., et al. 2015. Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. Field Crops Res. 175, 64–79. doi:10.1016/j.fcr.2015.01.012.
[56] Zander, P. Amjath-Babu, T.S., Preissel, S., Reckling, M., Bues, A., Schläfke, N., Kuhlman, T., Bachinger, J., Uthes, S., Murphy-Bokern, D., Stoddard, F., Watson, C.A. 2016. Grain legume decline and potential recovery in European agriculture: a review. Agron. Sust. Dev. 36,1–20. doi: 10.1007/s13593-016-0365-y.
[57] Del Grosso, S. J., Wirth, T., Ogle, S. M., Parton, W. J. 2008. Estimating Agricultural Nitrous Oxide Emissions. Eos Trans. AGU, 89 (51), 529– 529, doi:10.1029/2008EO510001.
[58] IPCC 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

the now increased value as there was evidence for greater emissions than so far assumed.[59] Next to soil nitrogen inputs through fertilisation, crop residues were also included as a nitrogen source and emissions modelled with the same EF. Impacts of environmental and soil conditions are hardly reflected within the tier 1 methodology which makes the results rather more approximations since there is a strong dependence of nitrous oxide emissions from these factors.[60] The applied default value in the Tier 1 methodology for any wet area in the world mainly emphasises the disadvantages of this approach and decreases the robustness of the results in terms of country specifics. Nevertheless, the method was applied in order to have a standard method across all sites which can be relatively simply applied and needs few input variables. As with all indicator results, the modelled emissions were checked by the regional data providers in order to secure plausible results. Discrepancies were only reported from the case study regions in north-western Europe in which an overestimation is possible, depicted also in efforts of the UK and Ireland to move to country-specific EFs.[61]

Mineral fertiliser production, with its high resource and energy use as well as emissions of nitrous oxide[62] (for some products) as a powerful GHG with an extremely high global warming potential, is the major source for detrimental impacts on climate from crop production. Nitrate leaching also causes major impacts. Leaching is impacted by several factors including the quantity of available nitrate in the soil, soil texture and structure and the volume of drainage water.[63] Due to the process of biological nitrogen fixation that leads to nitrogen-rich crop residues, legume cultivation is considered to bear the risk of higher nitrate leaching.[64] Not in the legume crop itself, but particularly in the period after the legume harvest when the nitrogen demand of the following crop is still low, leaching can be high.[65] Despite this risk assessment a recent study on European cropping systems has found that legume-supported systems had comparable or lower leaching rates.[66] The analysis of the Legumes Translated data set also showed that the average nitrate leaching in arable cropping systems with legumes was not increased but similar to the reference systems. In several case studies nitrate leaching was even reduced by up to 30% which was mainly caused by reduced rotational nitrogen inputs. In single examples with higher leaching rates the fertilisation rates were accordingly only minimally or not reduced. Moreover, the starter nitrogen inputs for legumes which were above the

[59] IPCC 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Switzerland: IPCC.

[60] Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R., Zechmeister-Boltenstern, S. 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philosophical Transactions of the Royal Society B Biological Sciences 368 (1621). doi: 10.1098/rstb.2013.0122.

[61] Thorman, R. E., Nicholson, F. A., Topp, C. F. E., Bell, M. J., Cardenas, L. M., Chadwick, D. R., Cloy, J. M., Misselbrook, T. H., Rees, R. M., Watson, C. J. and Willimas , J. R. 2020. Towards Country-Specific Nitrous Oxide Emission Factors for Manures Applied to Arable and Grassland Soils in the UK. Frontiers in Sustainable Food Systems. 4, p. 62. doi: 10.3389/fsufs.2020.00062.

[62] Hasler, K., Bröring, S., Omta, S.W.F., Olfs, H.-W. 2015. Life cycle assessment (LCA) of different fertilizer product types. European Journal of Agronomy. 69, 41-51. doi: 10.1016/j.eja.2015.06.001.

[63] Watson, C., et al. 2017. Grain legume production and use in European agricultural systems. Adv. Agron. 144, 235–303. doi:10.1023/A:1024847017371.

[64] Böhm, H. Dauber, J., Dehler, M., Gallardo, D., de Witte, T., Fuß, R., Höppner, F., Langhof, M., Rinke, N., Rodemann, B., Ruehl, G., Schittenhelm, S. 2020. Crop rotations with and without legumes: a review. Journal für Kulturpflanzen 72, 489-509. doi: 10.5073/JFK.2020.10-11.01.

[65] Nemecek, T., von Richthofen, J.S., Dubois, G., Casta, P., Charles, R., Pahl, H. 2008. Environmental impacts of introducing grain legumes into European crop rotations. European Journal of Agronomy 28, 380-393. doi: 10.1016/j.eja.2007.11.004.

[66] Reckling, M., Bergkvist, G., Watson, C., Stoddard, F., Zander, P. Walker, R., Pristeri, A., Toncea, I., Bachinger, J. 2016. Trade-Offs between Economic and Environmental Impacts of Introducing Legumes into Cropping Systems. Frontiers in Plant Science. 7. 669. 10.3389/fpls.2016.00669.

recommended quantities also impacted the higher losses because of an excessive nitrogen surplus. Management strategies such as early sowing of winter crops after legumes in order to prevent losses from nitrogen-rich residues, intercropping or the cultivation of catch and cover crops can decrease the risk of nitrate leaching.[59] In some case studies the integration of catch crops could reduce nitrate losses, however data providers from other regions reported that catch crops do not play a role which indicated the potential for optimizations of these cropping sequences with the introduction of catch crops, but also with the other named strategies.

Crop rotation design and management factors also determined the nitrate leaching in the forage cropping systems. In both case study regions the integration of alfalfa in the forage rotations resulted in lower nitrate leaching. The extremely reduced losses (63% lower) in Brandenburg (DE 40) were caused by the great differences in alfalfa and silage maize production. While maize received high nitrogen doses and left a winter fallow after harvest, alfalfa was unfertilised and allowed a continuous cover for the three years of cultivation and was thereby preventing large amounts of losses that mainly occurred during autumn and winter. In the grass-clover rotations from Scotland higher leaching values were found, however, caused by the introduction of winter wheat to these rotations that was not present in the reference system. The exchange of grass with grass-clover did not impact the rotational nitrate losses. Hence, the effect could in this example not be retraced to the legume introduction.

In the last decades agriculture has been characterized by a continuous trend towards specialized cropping systems that are dominated by cereals. A range of drivers led to a decreasing number of different crop species in rotations, monocultural cropping and uniform agricultural landscapes.[67] Legumes were in this context characterized as minor species contrasted against cereals as major species.[68] Following this marginalization of legumes, a rising legume production is seen as an increase of the diversity of crops in rotations temporally as well as spatially.[69] [70] Crop diversity that was assessed by the evaluation of temporal diversification through crop rotation design was also in the Legumes Translated data set significantly increased with the introduction of grain legumes in arable cropping systems. In forage cropping systems crop diversity was found to be similar in legume- and non-legume systems. The greatest effects were shown for legume integration in cereal-dominated rotations in which the introduction was recognized as a particularly valuable crop diversification practice. Benefits on associated diversity of wild flora, fauna and soil microbes were attested in a range of studies, but beyond the scope of the diversity assessment within the included indicator.[71] [72]

[67] Hufnagel, J., Reckling, M., Ewert, F. 2020. Diverse approaches to crop diversification in agricultural research. A review. Agronomy for Sustainable Development. 40. doi: 10.1007/s13593-020-00617-4.

[68] Magrini M.-B. et al. 2016. Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. Ecological Economics 126, 152–162. doi: 10.1016/j.ecolecon.2016.03.024

[69] Watson, C., et al. 2017. Grain legume production and use in European agricultural systems. Adv. Agron. 144, 235–303. doi:10.1023/A:1024847017371.

[70] Meynard, J.M., Messéan, A., Charlier, A., Charrier, F., 2013. Crop diversification: obstacles and levers. In: Fares,M., Le Bail, M.,Magrini, M.B., Savini, I. (Eds.), Study of farms and supply chains., Synopsis of the study carried out by INRA at the request of the ministries in charge of agriculture and ecology, INRA (62 pp. https://www6.paris.inra.fr/depe/Media/Fichier/Etudes/Diversification-des-cultures/synthese-anglais.). doi: 10.13140/RG.2.1.3473.3287.

[71] Böhm, H. et al. 2020. Crop rotations with and without legumes: a review. Journal für Kulturpflanzen 72, 489-509. doi: 10.5073/JFK.2020.10-11.01.

[72] Currently the Legumes Translated data set is prepared for an additional biodiversity assessment with the SALCA methods.

Legumes are, due to their higher protein content and complementary amino acid profiles to those in cereals, a valuable protein source for food and feed. While grain legumes protein content range between 20%-25% in common bean, pea and lentil, up to over 40% in yellow lupin and soybean, cereals only contain between 7%-17% protein.[73] The higher protein content comes along with less energy left for carbohydrate and general biomass production, which is one reason for lower yield level of legumes compared to cereals.[74] However, despite significantly lower grain yields of legumes compared to cereals, the total protein yields of legume crops were found to be higher than those of cereals crops.[75] Moreover, in legume-supported cropping systems there was evidence found for an increased protein content of following cereal crops.[76] [77] However, focusing on the energy output, legumes' advantages are smaller. Because of legumes' comparable gross energy content to cereals and their significantly lower yield levels, the energy yields of legume-supported rotations compared to typical cereal-based rotations without grain legumes were found to be smaller.[78] The analysis of the Legumes Translated data set supported these findings on higher protein and lower energy output of cropping systems with legumes. On average, protein yields were increased by 13% and 5% while energy output was reduced by 10% and 9% in arable and forage systems with legumes. Thus, the introduction of legumes into cropping systems resulted in a trade-off between protein and energy outputs. Considering, however, the European production deficit of plant proteins and dependency on imports, contrasted with the specialization in high-yielding cereal production and net export of cereals,[79] this trade-off seems tolerable and can be rather understood as a chance to promote Europe's protein self-sufficiency.

Yield stability is generally considered as a drawback in legume cultivation and legume yields were described as volatile and insecure.[80] Reasons were named with the indeterminate growth rate of grain legumes or the relative lack of breeding efforts for stress resistance.[81] The topic is also of high interest within the actor groups from Legumes Translated and considered as an essential barrier for increasing legume production. However, recent evaluations have shown that yield fluctuations of legumes were overestimated and were – when applying appropriate stability parameters - similar to those of other spring crops.[82] In the analysis of the Legumes Translated data set, yield stability was also found to be similar in arable as well as forage cropping systems with and without legumes, indicating that there is no increase in the production risk through

[73] Watson, C., et al. 2017. Grain legume production and use in European agricultural systems. Adv. Agron. 144, 235–303. doi:10.1023/A:1024847017371.

[74] Murphy-Bokern, D. Peeters, A. Westhoek, H. 2017. The Role of Legumes in Bringing Protein to the Table. In: Murphy-Bokern, D., Stoddard, F., Watson, C. (Eds.), Legumes in cropping systems. CABI, Oxon.

[75] Reckling, M., Döring, T.F., Bergkvist, G., Stoddard, F.L., Watson, C.A., Seddig, S., Chmielewski, F.-M., Bachinger, J.,2018. Grain legume yields are as stable as other spring crops in long-term experiments across northern Europe. Agron. Sustain. Dev. 38, 63. doi: 10.1007/s13593-018-0541-3

[76] Albrecht, R., Guddat, C., 2004. Welchen Wert haben Körnerleguminosen inder Fruchtfolge. Thüringer Landesanstalt für Landwirtschaft, pp. 7. http://www.tll.de/ainfo/pdf/kleg0104.pdf.

[77] Such effects were not considered in the multi-criteria assessment.

[78] Nemecek, T., et al. 2008. Environmental impacts of introducing grain legumes into European crop rotations. European Journal of Agronomy 28, 380-393, doi: 10.1016/j.eja.2007.11.004.

[79] Murphy-Bokern, D., et al. 2017. The Role of Legumes in Bringing Protein to the Table. In: Murphy-Bokern, D., Stoddard, F., Watson, C. (Eds.), Legumes in cropping systems. CABI, Oxon.

[80] Cernay C., Ben-Ari T., Pelzer E., Meynard J-M., Makowski D. 2015. Estimating variability in grain legume yields across Europe and the Americas. Scientific Reports 5: 11171. doi:10.1038/srep11171

[81] Watson, C., et al. 2017. Grain legume production and use in European agricultural systems. Adv. Agron. 144, 235–303. doi:10.1023/A:1024847017371.

[82] Reckling, M., et al.2018. Grain legume yields are as stable as other spring crops in long-term experiments across northern Europe. Agron. Sustain. Dev. 38, 63. doi: 10.1007/s13593-018-0541-3.

the integration of legumes in cropping systems. This quantitative evidence is sharply contrasting with the negative perception of farmers who still name yield instability as one of the most important disadvantage of legume cultivation.[83]

Perceived issues with yield stability are also often named in discussions about legumes' poor economic performance. Studies and reviews on the crop-level profitability have shown that legumes other than soybean have gross margin deficits compared to alternative crops.[84] [85] [86] Next to lower prices and the generally lower yield level of legumes, the volatility of yields and hence also revenues are named as key drivers.[87] These drawbacks in the economic performance of legumes are understood as the major explanation for the low legume cropping shares in Europe. Despite the range of environmental benefits and contributions to ESS provision that legumes make, farmers do not integrate them into cropping systems, as the trade-offs between environmental and economic impacts are perceived as too severe. However, the economic assessment of legumes changes when not the crop-level, but the rotational-level profitability is considered and the pre-crop effects that can contribute to higher revenues and lower production costs of subsequent crops are integrated in the evaluation. A meta-analysis of European studies has shown that the competitiveness of grain legumes was clearly raised when assessing whole rotations.[88] The evaluation of the Legumes Translated data set showed on average similar standard GMs in arable cropping systems with and without legumes and in terms of the forage cropping systems an economic advantage for legume-supported systems. Considerations of the single case studies displayed that in nine of the 17 case study regions legume-supported cropping systems were competitive to the reference systems. The other case studies showed in most examples reductions in the standard GM between only 2% to 35%. With the substitution of the reported legume prices with the calculated feed values it was illustrated that rising prices of pea, faba bean and lupin would have a significant effect on the rotational profitability of legume systems. This scenario of rising prices can become relevant in the long-term with increasing development of markets and value chains for European legumes, however, for balancing GM deficits in the short-term, policy measures with immediate effect are important. Impacts from legume-supporting instruments of the CAP in the 2014-2020 period were analyzed and showed to contribute considerably to the competitiveness of rotations with legumes which is why intentions to foster legumes also in the following CAP period with the inclusion in eco-schemes are an important signal. The potential support for legume cultivation through further policy instruments was integrated in the analysis with a carbon tax on the production of mineral fertiliser. Cropping systems with particular high fertilisation savings profited most and it could be shown that focusing on the integration of externalities and express legumes' non-market outputs in financial terms can be a valuable tool in order to incentivize legume cultivation.

[83] Watson, C. 2021. Raising the pulse. Presentation at SLU Crop Production Ecology Seminar: Raising the pulse of cropping systems; Constraints and opportunities for legume production in Northern Europe.
[84] Preissel, S., Reckling, M., Bachinger, J., Zander, P. 2017. Introducing legumes into European cropping systems: farm-level economic effects, in: Murphy-Bokern, D., Stoddard, F.L., Watson, C.A. (Eds.), Legumes in cropping systems. CABI Publishing, 209–225.
[85] Böhm, H. et al. 2020. Crop rotations with and without legumes: a review. Journal für Kulturpflanzen 72, 489-509. doi: 10.5073/JFK.2020.10-11.01.
[86] The assessment of legume profitability on the crop-level performed in Deliverable Report 4.2 showed similar results for the Legumes Translated data set.
[87] Zander, P. et al. 2016. Grain legume decline and potential recovery in European agriculture: a review. Agron. Sust. Dev. 36,1–20. doi: 10.1007/s13593-016-0365-y.
[88] Preissel, S., et al. 2015. Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. Field Crops Res. 175, 64–79. doi:10.1016/j.fcr.2015.01.012.

Within the present analysis several of these non-market outputs of legumes were depicted in the assessment indicators, however, other impacts such as enhancement of the above and below ground biodiversity, effects on the soil quality, phytosanitary risk reductions or the emission reductions by the substitution of imported soybean with European legumes were not explicitly integrated in the evaluation.[89] Therefore, final assessments of the potential of the considered legume-supported rotations need to note also these additional effects.

The evaluation of 11 indicators has allowed the comparison of cropping systems with legumes to reference cropping systems without legumes in regional case studies and has illustrated, thereby, costs and benefits of the legume integration. While in almost all case studies clear advantages in the environmental impact area could be noticed for the legume-supported systems, not all examples showed competitive results to their reference systems in the economic area, due to foregone rotational revenues. But these trade-offs could be reduced when modifying the standard GM with the consideration of subsidies, feed value and carbon taxes, emphasizing the need for legume price developments and policy support.

Low trade-offs or even win-win situations between economic and environmental impacts were particularly found in two situations in the considered arable cropping systems. On the one hand soybean-supported cropping systems were beneficial in both impact areas, since soybean achieved high prices and secured high profitability, as it was given in Austria, Italy, Serbia and Ukraine. On the other hand regions where grain legume yields were relatively high, as for example shown with high-yielding faba bean in Ireland and Scotland, environmental benefits were also secured while offering concomitantly economically attractive cropping options. These identifications of win-win situations showed that high economic performance is not necessarily combined with high input use and signalled potential alternative cropping strategies for reducing the depletion of resources and the environmental impacts of agriculture without generating economic losses for farmers. Integrating the results from the impact area of production in the consideration of trade-offs, showed that due to the assessed similar yield stability, increased protein output and decreased energy output in most legume-supported systems, the above outlined win-win situations between economic and environmental impacts were further expanded by an additional gain in productivity in terms of protein production with no associated increased risk in production in terms of yield stability. Trade-offs only had to be made for lower energy outputs. Former studies have shown that win-win situations between environmental benefits and financial attractiveness were more likely to be found in forage legume cropping systems comparisons due to their better economic and environmental performance.[90] This was also found for five of the seven compared cropping systems with forage legumes in the Legumes Translated data set, however, these win-win situations were restricted to the environmental indicators of nitrogen fertiliser use and nitrous oxide emissions, since the additional introduction of winter wheat negatively impacted the results of nitrate leaching and protein output. Trade-offs between economic and environmental impacts in the Scottish alfalfa rotation were higher due to the important agronomic constraint of crop establishment in forage

[89] Soil C and additional biodiversity assessments are currently in work.
[90] Reckling, M., et al. 2016. Trade-Offs between Economic and Environmental Impacts of Introducing Legumes into Cropping Systems. Frontiers in Plant Science. 7. 669. doi: 10.3389/fpls.2016.00669.

legume production that was also reflected in the economic as well as production-related assessment. But the assessment of trade-offs and win-win situations in forage cropping systems are also matter of particular farming type or farm cooperations, because forage legume integration is only suitable for mixed farms.

**Limitations of data**

Due to the approach to compile relevant cropping systems with and without legumes from the actor groups within Legumes Translated that depicted their experiences and practices in legume cultivation, but also other cropping patterns, there were some limitiations in the collected data. Reference systems were in several cases not only modified by the legume introduction, but also greater changes in the rotation design which reduced in some examples the comparability of the rotations and reduced the effect of the legume integration due to confounding factors. This was particularly apparent, for instance, in the Scottish forage cropping systems, in which the additional introduction of winter wheat to the legume rotations had stronger effects than the substitution of grass with grass-clover. However, such constellations and impacts were stressed in the results analysis in order to prevent misleading understanding of results. Moreover, the approach to assess locally relevant cropping systems and not systematically designed cropping systems is also seen as primarily stimulating actual discussion in the case study regions on the assessed opportunities for diversification and secondly for allowing static comparisons. The diverse compilation approaches and data backgrounds also prevented a common approach for the quantification of legumes' pre-crop effects. Comparisons can only be done within the regional contexts which limited the analysis of size and value of legume effects across regions.

# Conclusion

Legumes can considerably increase the sustainability of agro-ecosystems and make valuable contributions to a range of ESS. A cropping system perspective is needed to evaluate the complex and range of impacts of legumes. This enables a realistic view on their contributions to farming systems. Due to the currently low cropping shares of legumes in European agricultural systems, experiences and practice-based data on legume-supported cropping systems are scarce. However, the range of legume-experienced actors within the multi-actor project Legumes Translated allowed us to compile the knowledge and experiences of these experts and provided the ideal basis for assessing the role of legumes in crop rotations of real farm situations.

The comparisons between reference cropping systems without legumes and legume-supported systems showed that the latter had advantages in the environmental impact area with lower nitrogen fertiliser use, lower nitrous oxide emissions, increased crop diversity and in some cases also decreased nitrate leaching. Economic benefits were found particularly in soybean-supported systems and rotations with high-yielding legumes. The economic performance clearly increased when considering the legume feed value, subsidies and carbon taxes and more legume-supported systems became competitive to their reference systems. The common negative perception that legumes increase the production risk due to higher yield volatility was not confirmed in the assessment of yield stability at cropping system scale. Protein output was found to be increased in legume-supported systems which displayed the potential for contributing in part to Europe's protein self-sufficiency, however with a trade-off for lower food or feed energy yields.

The analysis outlined several cases where legumes led to win-win situations or only minor trade-offs between the evaluated impact areas and presented potential alternative cropping strategies that can be communicated within and beyond the actor groups. Some management changes and crop design optimisations such as the consideration of positive pre-crop benefits on yield and fertilisation planning could further strengthen the positive effects from legume cropping. Moreover, various external factors can also enhance the positive impacts and reduce potential economic disadvantages from legume rotations. Policy support either via direct payments within the voluntary coupled support (VCS), country or region specific environmental payment schemes such as the support for "diverse crop rotations" with a minimum share of legumes in some German states or indirectly via financially valuing ecosystem service provision of legumes is an important element in fostering legume profitability. The development of new market outlets and value chains for European legumes will help correct the current economic under-valuation of legumes and could increase the market prices. Additionally, advances in legume breeding and improvements in agronomy can improve the productivity and performance in legume cropping.

This work on the multi-criteria assessment of project partners' cropping systems is an example of the project's co-learning cycles working to combine the insights of differing actor groups within a robust analytical framework. It supported the illustration and reflection of legume impacts in tangible indicators as well as the communication in the case study regions on opportunities and constraints of legume-supported cropping systems.

Further plans for dissemination include the hosting of a webinar for the Legumes Translated consortium for the purpose of sharing and discussing the results based on the presentation of the summarized findings in this deliverable report. Subsequently, the translation and processing of the results in further Legumes Translated publishing formats is planned in order to break down the detailed findings and make them accessible for a broader range of stakeholders. In terms of the academic dissemination a scientific paper on the findings of the multi-criteria assessment is planned as well as a joint conference contribution with all data providing partners in the Landscape 2021 conference.[91]

[91] https://www.landscape2021.org/frontend/index.php.

**ACKNOWLEDGMENTS**

We also thank Blackert, B., Fricke-Müller, M., Heimel, P., Hufnagel, J., Korchahina, I., Lazzari, F., Milev, G., Nußbaumer, H., Pochiscanu-Isticioaia, S., Radiuk, A., Rosner, G., Rezi, R., Todorova, R., Rüdiger, G., Vasileva, V., Wille, R. for providing and discussing data on cropping systems.

# Annex I

Table 7. Included countries and regions from data providing actor groups

| Country | NUTS 2 code | Region | Actor Group |
|---|---|---|---|
| Central-eastern Europe | | | |
| Bulgaria | BG 31 | Severozapaden | Bulgarian legumes network |
| | BG 32 | Severen Tsentralen | Bulgarian legumes network |
| | BG 33 | Severoiztochen | Bulgarian legumes network |
| Romania | RO 11 | North-West | Europe Soya Value Chain Development Group |
| | RO 21 | North-East | Europe Soya Value Chain Development Group |
| Serbia | RS 12 | Region Vojvodine | Soybean Cultivation Group in South east Europe |
| Ukraine | | Kyiv oblast | Europe Soya Value Chain Development Group |
| Central-western Europe | | | |
| Austria | AT 11 | Burgenland | Europe Soya Value Chain Development Group |
| | AT 12 | Niederösterreich | Europe Soya Value Chain Development Group |
| Germany | DE 11 | Stuttgart (Hohenlohekreis) | Schwäbisch Hall Producers |
| | DE 13 | Freiburg (Markgräflerland) | German Soybean Association |
| | DE 40 | Brandenburg | Brandenburg Farmers' Network |
| | DE 73 | Nordhessen | German Pea and Bean Network |
| North-western Europe | | | |
| United Kingdom | UKM 7 | Eastern Scotland | SRUC Dairy Protein Group |
| United Kingdom | UKM 9 | Southern Scotland | SRUC Dairy Protein Group |
| Ireland | IE 05, IE 06 | Southern, Eastern and Midland | The Irish Grain Legumes Group |
| Southern Europe | | | |
| Italy | ITH 4 | Friuli-Venezia Giulia | Europe Soya Value Chain Development Group |

## Annex II

Table 8. All actor groups within Legumes Translated

| Name | Country | Representing consortium partner | Involved organizations/ members | Specific legume interest |
|---|---|---|---|---|
| Bulgarian legumes network | Bulgaria | AgroBioInstitute | Researchers, breeders, growers, e.g. Dobrudzha Agricultural Institute (DAI) General Toshevo, Experimental Station for Soybean (ESS) Pavlikeni, Institute of Forage Crops (IFC) Pleven | Breeding of legumes varieties, development of sustainable agro technology for created varieties, processing and use of legumes as a feed and food |
| German Soybean Association | Germany | Centre for Agricultural Technology Augustenberg (LTZ) | Farmers (conventional and organic), advisors, agronomists, breeders and private individuals as well as companies (breeding, transformation into feed and food, cooperatives, machinery etc.) | Improvement of cultivation and processing of soybeans in Germany |
| Soy Network Switzerland | Switzerland | Research Institute of Organic Agriculture FiBL | FiBL, Agroscope, Delley Samen and Pflanzen AG, Progana, Bio Ackerbauring Ostschweiz, Bio Suisse, Mühle Rytz | Establish and promote organic soy for feed and food from Switzerland |
| Schwäbisch Hall Producers | Germany | Schwäbisch Hall Producers (BESH) | Livestock farmers, Landwirtschaftliche Beratungsdienst Schwäbisch Hall, stakeholders along the feed supply chain soy | Locally grown legumes for feed |
| Soybean Cultivation Group in South east Europe | South-Eastern Europe | Institute of Field and Vegetable Crops | Farmers and research-based actors | Soybean cultivation in Serbia |
| Europe Soya Value Chain Development Group | Danube region | Donau Soja | Farmers (crop and livestock producers) and feed & food processors (SMEs), link to researchers and technology providers | Further development of soya production in Danube region and link to new value chains for livestock production |
| The German Lupin Network | Germany | Leibniz Centre for Agricultural Landscape Research (ZALF) | Farmers, state research centres, advice centres, breeders, processors and trading companies | Support the growth of lupin cultivation and development of relevant value chains |
| German Pea and Bean Network | Germany | Hessen Department of Agricultural Affairs (LLH) | Farmers, state institutions, universities, associations and a private institute | Expanding and improving cultivation and utilisation of peas and beans |
| Swiss Lupin Network | Switzerland | Research Institute of Organic Agriculture FiBL | Partners from the entire (organic) lupin production chain | Establish sweet lupin as a valuable domestic food and feed crop in Swizerland |
| Brandenburg Farmers' Network | Germany | Leibniz Centre for Agricultural Landscape Research | Farmers, researchers | Legume-supported cropping systems including grain legumes (lupin, pea, soybean) and perennial forage crops (legume-grass, alfalfa) |

| | | | | |
|---|---|---|---|---|
| | | (ZALF) | | |
| The Irish Grain Legumes Group | Ireland | Teagasc | Agents of seed sector (Seedtech), agricultural suppliers, farming community, research, technology transfer, food and feed industries | Crop management of faba beans and other relevant crops, production input, financial performance, resource and environmental data |
| SRUC Dairy Protein Group | United Kingdom | Scotland’s Rural College (SRUC) | SRUC consultants and researchers, expertise from milk purchasers, feed supply companies, forage and plant breeding companies and veterinary surgeons | Optimization of protein use, replacement of purchased protein feeds by home-grown sources with particular emphasis on white clover |
| LegumesForFish | Greece | NIREUS Aquaculture | NIREUS Group, THESGI Farmers' Cooperative of Thessaly, The Department of Biochemistry & Biotechnology, University of Thessaly (UTH) | Legumes in the production of fish feeds |
| Ground for Growth | Finland | University of Helsinki | Diverse actors along food chain - farmers’ networks, consumers' networks, processors, scientists, etc. | Pulses that can be cultivated in Finland: Faba bean, pea and lupin |

**Annex III**

In course of the data collection, several practical issues became visible and an iterative process of data gathering and checking was initialized. Considering the responses to the data request, a list of questions was formulated in order to address and discuss the different issues:

- Is one rotation without and one with legumes defined and are the rotations comparable?

In some case study regions, actor groups could only refer to rotations with legumes due to regional specifics or the field of action of the actor groups. This was tried to be solved by jointly determining theoretical rotations without legumes or referring to practices outside the actor groups.

In terms of the time frame it was essential to remind data providers to collect data for all rotations from the same years to prevent effects of year-specific particularities.

- Do the defined crop sequences comply with rotational restrictions as minimum sequential break of crops, maximum frequency of a crop/crop type, and suitability of crop-crop combinations considering phytosanitary/timing constraints?

- Are the crop management data complete and plausible in terms of clear indication of the inputs i.e. seed, fertiliser and plant protection?

- Are the crop management data complete and plausible in terms of cover crops and tillage?

- Do the crop management data include adapted management depending on the pre-crops and take pre-crop effects on yield, fertiliser, plant protection and potentially tillage into account?

- Are costs and prices plausible and coherent throughout the provided data (same time period, same prices for the rotations with/without legumes etc.)?

- Are long-term yield data used for analyzing yield stability provided for all crops in the crop sequences?

The provided data were checked on those questions and bilateral communication on ambiguities in the data with subsequent corrections or explanations by the data providers were recorded. In some cases trade-offs had to be made between having rotation pairs that on the one hand follow crop rotation rules and are as similar as possible and on the other hand display regional practices. However, it was secured to have always rotations that allow comparisons, even though the differences could not in all examples be exclusively traced back to the presence of the legume alone.

## Annex IV

Table 9. Economic impact assessment of reference and legume-supported arable cropping systems in case study regions in central-eastern Europe

| Region | +/- leg-ume | C1 | C2 | C3 | C4 | C5 | C6 | GM (stan-dard) [€/ha] | GM (feed value) [€/ha] | GM (sub-sidies) [€/ha] | GM ($CO_2$-tax I) [€/ha] | GM ($CO_2$-tax II) [€/ha] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Arable cropping systems*** | | | | | | | | | | | | |
| **Central-eastern Europe** | | | | | | | | | | | | |
| BG, BG 31 | - | WW | GM | SF | | | | 472 | 472 | 472 | 352 | 432 |
| | + | FP | WW | GM | SF | | | 366 | 447 | 407 | 280 | 338 |
| | + | WW | SF | FP | GM | | | 394 | 475 | 417 | 308 | 365 |
| BG, BG 32 | - | WOR | WW | SF | GM | | | 656 | 656 | 656 | 555 | 622 |
| | + | SY | WW | SF | WW | | | 643 | 643 | 670 | 596 | 627 |
| BG, BG 33 | - | WOR | WW | SF | GM | | | 589 | 589 | 589 | 487 | 555 |
| | + | CB | WW | SF | WW | | | -71 | -71 | -43 | -166 | -102 |
| RO, RO 11 | - | GM | WW | | | | | 266 | 266 | 266 | 161 | 231 |
| | | GM | WW | SY | | | | 256 | 256 | 327 | 190 | 234 |
| RO, RO 21 | - | GM | SF | WW | | | | 540 | 540 | 540 | 470 | 516 |
| | + | GM | WW | SY | | | | 605 | 605 | 676 | 535 | 582 |
| RS, RS 12 | - | GM | WW | | | | | 361 | 361 | - | 266 | 329 |
| | + | GM | WW | SY | | | | 612 | 612 | - | 535 | 586 |
| UA, Kyiv oblast | - | GM | SF | WW | | | | 650 | 650 | - | 556 | 619 |
| | + | GM | SY | SF | WW | | | 683 | 683 | - | 608 | 658 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 10. Economic impact assessment of reference and legume-supported arable cropping systems in case study regions in central-western Europe

| Region | +/- leg-ume | C1 | C2 | C3 | C4 | C5 | C6 | GM (stan-dard) [€/ha] | GM (feed value) [€/ha] | GM (sub-sidies) [€/ha] | GM (CO2-tax I) [€/ha] | GM (CO2-tax II) [€/ha] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Arable cropping systems*** | | | | | | | | | | | | |
| **Central-western Europe** | | | | | | | | | | | | |
| AT, AT 11 | - | GM | GM | WW | | | | 440 | 440 | 440 | 298 | 393 |
| | + | SY | WW | GM | | | | 688 | 688 | 688 | 605 | 660 |
| AT, AT 12 | - | GM | WW | SF | | | | 507 | 507 | 507 | 403 | 472 |
| | + | GM | WW | SY | | | | 544 | 544 | 544 | 457 | 515 |
| DE, DE 11 | - | WW | WB | TR | | | | 172 | 172 | 172 | 107 | 150 |
| | + | WW | WB | FP | TR | | | 136 | 173 | 211 | 92 | 121 |
| DE, DE 11 | - | SU | WW | WB | GM | | | 331 | 331 | 331 | 283 | 315 |
| | + | SU | WW | WB | FB | | | 214 | 266 | 289 | 174 | 201 |
| DE, DE 13 (gravel) | - | GM | GM | WW | WOR | | | 326 | 326 | 326 | 206 | 286 |
| | + | GM | GM | SY | WW | WOR | | 284 | 284 | 359 | 192 | 253 |
| DE, DE 13 (silt) | - | GM | GM | WW | WOR | | | 711 | 711 | 711 | 574 | 665 |
| | + | GM | GM | SY | WW | WOR | | 652 | 652 | 727 | 545 | 616 |
| DE, DE 40 (soil type 2) | - | WW | WB | WOR | | | | 448 | 448 | - | 331 | 409 |
| | + | WW | FP | WW | WB | WOR | | 388 | 426 | - | 298 | 358 |
| | + | WW | SY | WW | WB | WOR | | 431 | 431 | - | 341 | 401 |
| DE, DE 40 (soil type 3) | - | WR | WR | WOR | | | | 390 | 390 | - | 291 | 357 |
| | + | WR | FP | WR | WOR | | | 332 | 371 | - | 258 | 307 |
| | + | WR | L | WR | WOR | | | 328 | 349 | - | 254 | 303 |
| DE, DE 73 | - | WOR | WW | WW | SB | | | 250 | 250 | 250 | 107 | 202 |
| | + | WOR | WW | FP | WW | SB | | 190 | 234 | 300 | 76 | 152 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 11. Economic impact assessment of reference and legume-supported arable cropping systems in case study regions in north-western and southern Europe

| Region | +/- leg-ume | C1 | C2 | C3 | C4 | C5 | C6 | GM (stan-dard) [€/ha] | GM (feed value) [€/ha] | GM (sub-sidies) [€/ha] | GM (CO2-tax I) [€/ha] | GM (CO2-tax II) [€/ha] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Arable cropping systems*** | | | | | | | | | | | | |
| **North-western Europe** | | | | | | | | | | | | |
| GB, UKM 7 | - | WOR | WB | WO | SB | WB | | 819 | 819 | - | 683 | 774 |
| | + | WOR | WB | WO | FP | WB | | 820 | 852 | - | 718 | 786 |
| | + | WOR | WB | WO | FB | SB | | 831 | 870 | - | 733 | 798 |
| IE, IE 05, IE, 06 | - | WB | WO | WW | WB | WOR | WW | 502 | 502 | 502 | 333 | 445 |
| | + | WB | WO | WW | FB | WW | | 464 | 589 | 523 | 332 | 420 |
| IE, IE 05, IE, 06 | - | SMB | SO | SFB | SMB | SMB | | 337 | 337 | 337 | 218 | 298 |
| | + | SMB | FB | SO | SFB | SMB | | 360 | 484 | 418 | 263 | 328 |
| **Southern Europe** | | | | | | | | | | | | |
| IT, ITH 4 | - | GM | GM | GM | | | | 292 | 292 | 292 | 91 | 225 |
| | + | GM | SY | | | | | 562 | 562 | 599 | 459 | 528 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 12. Economic impact assessment of reference and legume-supported forage cropping systems in case study regions in central-western and north-western Europe

| Region | +/- leg-ume | C1 | C2 | C3 | C4 | C5 | C6 | GM (stan-dard) [€/ha] | GM (feed value) [€/ha] | GM (sub-sidies) [€/ha] | GM (CO2-tax I) [€/ha] | GM (CO2-tax II) [€/ha] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Forage cropping systems*** | | | | | | | | | | | | |
| **Central-western Europe** | | | | | | | | | | | | |
| DE, DE 40 | - | WW | WR | SM | SM | SM | | 420 | 420 | - | 336 | 392 |
| | + | WW | WR | AF | AF | AF | | 360 | 360 | - | 320 | 347 |
| **North-western Europe** | | | | | | | | | | | | |
| GB, UKM 9 | - | GR | GR | GR | SB | | | 128 | 128 | - | 62 | 106 |
| | + | GC | GC | GC | WW | | | 266 | 266 | - | 232 | 255 |
| | + | GC | GC | GC | SB | FP/SB | WW | 218 | 218 | - | 186 | 208 |
| | + | GC | GC | GC | SB | FP | WW | 211 | 211 | - | 178 | 200 |
| | + | GC | GC | GC | SB | FB | WW | 299 | 332 | - | 270 | 289 |
| | + | AF | AF | AF | SB | | | 5 | 5 | - | 1 | 3 |
| | + | WW | GC | GC | GC | SB | | 213 | 213 | - | 174 | 200 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 13. Environmental impact assessment of reference and legume-supported arable cropping systems in case study regions in central-eastern Europe

| Region | +/- legume | C1 | C2 | C3 | C4 | C5 | C6 | NO3-N [kg/ha] | N fertiliser use [kg/ha] | N2O emissions [kg/ha] | Crop diversity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Arable cropping systems*** | | | | | | | | | | | |
| **Central-eastern Europe** | | | | | | | | | | | |
| BG, BG 31 | - | WW | GM | SF | | | | 40 | 143 | 5.0 | 0.63 |
| | + | FP | WW | GM | SF | | | 34 | 102 | 3.8 | 1.04 |
| | + | WW | SF | FP | GM | | | 36 | 102 | 3.8 | 1.04 |
| BG, BG 32 | - | WOR | WW | SF | GM | | | 22 | 120 | 4.1 | 0.63 |
| | + | SY | WW | SF | WW | | | 20 | 55 | 2.2 | 0.73 |
| BG, BG 33 | - | WOR | WW | SF | GM | | | 22 | 120 | 4.1 | 0.69 |
| | + | CB | WW | SF | WW | | | 41 | 114 | 4.1 | 1.04 |
| RO, RO 11 | - | GM | WW | | | | | 20 | 125 | 4.2 | 0.00 |
| | | GM | WW | SY | | | | 18 | 79 | 2.9 | 0.63 |
| RO, RO 21 | - | GM | SF | WW | | | | 30 | 83 | 3.2 | 0.63 |
| | + | GM | WW | SY | | | | 37 | 83 | 3.5 | 0.63 |
| RS, RS 12 | - | GM | WW | | | | | 50 | 112 | 4.3 | 0.00 |
| | + | GM | WW | SY | | | | 45 | 91 | 4.0 | 0.63 |
| UA, Kyiv oblast | - | GM | SF | WW | | | | 37 | 111 | 4.2 | 0.63 |
| | + | GM | SY | SF | WW | | | 41 | 89 | 3.7 | 1.04 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 14. Environmental impact assessment of reference and legume-supported arable cropping systems in case study regions in central-western Europe

| Region | +/- leg-ume | C1 | C2 | C3 | C4 | C5 | C6 | NO3-N [kg/ha] | N fertiliser use [kg/ha] | N2O emissions [kg/ha] | Crop diversity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Arable cropping systems*** | | | | | | | | | | | |
| **Central-western Europe** | | | | | | | | | | | |
| AT, AT 11 | - | GM | GM | WW | | | | 34 | 169 | 5.7 | 0.00 |
| | + | SY | WW | GM | | | | 34 | 99 | 3.9 | 0.63 |
| AT, AT 12 | - | GM | WW | SF | | | | 30 | 123 | 4.3 | 0.63 |
| | + | GM | WW | SY | | | | 39 | 103 | 4.0 | 0.63 |
| DE, DE 11 | - | WW | WB | TR | | | | 29 | 173 | 4.7 | 0.00 |
| | + | WW | WB | FP | TR | | | 26 | 123 | 3.6 | 0.56 |
| DE, DE 11 | - | SU | WW | WB | GM | | | 12 | 153 | 4.2 | 0.56 |
| | + | SU | WW | WB | FB | | | 21 | 95 | 3.4 | 1.04 |
| DE, DE 13 (gravel) | - | GM | GM | WW | WOR | | | 14 | 175 | 5.2 | 0.56 |
| | + | GM | GM | SY | WW | WOR | | 14 | 136 | 4.2 | 0.95 |
| DE, DE 13 (silt) | - | GM | GM | WW | WOR | | | 17 | 195 | 6.0 | 0.56 |
| | + | GM | GM | SY | WW | WOR | | 17 | 152 | 4.9 | 0.95 |
| DE, DE 40 (soil type 2) | - | WW | WB | WOR | | | | 43 | 139 | 5.0 | 0.56 |
| | + | WW | FP | WW | WB | WOR | | 35 | 107 | 4.0 | 0.95 |
| | + | WW | SY | WW | WB | WOR | | 36 | 107 | 4.0 | 0.95 |
| DE, DE 40 (soil type 3) | - | WR | WR | WOR | | | | 47 | 118 | 4.4 | 0.63 |
| | + | WR | FP | WR | WOR | | | 38 | 86 | 3.4 | 1.04 |
| | + | WR | L | WR | WOR | | | 40 | 86 | 3.4 | 1.04 |
| DE, DE 73 | - | WOR | WW | WW | SB | | | 51 | 170 | 6.4 | 0.56 |
| | + | WOR | WW | FP | WW | SB | | 43 | 135 | 5.3 | 0.95 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 15. Environmental impact assessment of reference and legume-supported arable cropping systems in case study regions in north-western and southern Europe

| Region | +/- leg-ume | C1 | C2 | C3 | C4 | C5 | C6 | NO3-N [kg/ha] | N fertiliser use [kg/ha] | N2O emissions [kg/ha] | Crop diversity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Arable cropping systems*** | | | | | | | | | | | |
| **North-western Europe** | | | | | | | | | | | |
| GB, UKM 7 | - | WOR | WB | WO | SB | WB | | 44 | 174 | 5.8 | 0.50 |
| | + | WOR | WB | WO | FP | WB | | 33 | 121 | 4.4 | 0.95 |
| | + | WOR | WB | WO | FB | SB | | 32 | 128 | 4.3 | 0.95 |
| IE, IE 05, IE, 06 | - | WB | WO | WW | WB | WOR | WW | 62 | 200 | 7.2 | 0.46 |
| | + | WB | WO | WW | FB | WW | | 47 | 157 | 5.8 | 0.50 |
| IE, IE 05, IE, 06 | - | SMB | SO | SFB | SMB | SMB | | 52 | 142 | 5.3 | 0.00 |
| | + | SMB | FB | SO | SFB | SMB | | 48 | 114 | 4.6 | 0.50 |
| **Southern Europe** | | | | | | | | | | | |
| IT, ITH 4 | - | GM | GM | GM | | | | 65 | 265 | 9.1 | 0.00 |
| | + | GM | SY | | | | | 46 | 123 | 3.4 | 0.69 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 16. Environmental impact assessment of reference and legume-supported forage cropping systems in case study regions in central-western and north-western Europe

| Region | +/- leg-ume | C1 | C2 | C3 | C4 | C5 | C6 | NO3-N [kg/ha] | N fertiliser use [kg/ha] | N2O emissions [kg/ha] | Crop diversity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Forage cropping systems*** | | | | | | | | | | | |
| **Central-western Europe** | | | | | | | | | | | |
| DE, DE 40 | - | WW | WR | SM | SM | SM | | 42 | 168 | 5.2 | 0.67 |
| | + | WW | WR | AF | AF | AF | | 16 | 47 | 3.5 | 0.67 |
| **North-western Europe** | | | | | | | | | | | |
| GB, UKM 9 | - | GR | GR | GR | SB | | | 9 | 151 | 4.5 | 0.6 |
| | + | GC | GC | GC | WW | | | 11 | 114 | 3.9 | 0.6 |
| | + | GC | GC | GC | SB | FP/SB | WW | 12 | 97 | 3.6 | 0.6 |
| | + | GC | GC | GC | SB | FP | WW | 11 | 97 | 3.6 | 0.6 |
| | + | GC | GC | GC | SB | FB | WW | 11 | 94 | 3.4 | 0.6 |
| | + | AF | AF | AF | SB | | | 6 | 19 | 1.7 | 0.6 |
| | + | WW | GC | GC | GC | SB | | 13 | 117 | 3.9 | 0.7 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 17. Production-related impact assessment of reference and legume-supported arable cropping systems in case study regions in central-eastern and central-western Europe

| Region | +/- legume | C1 | C2 | C3 | C4 | C5 | C6 | Yield stability (CV) | Protein output [kg/ha] | Energy output [GJ/ha] |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Arable cropping systems*** | | | | | | | | | | |
| **Central-eastern Europe** | | | | | | | | | | |
| BG, BG 31 | - | WW | GM | SF | | | | 11% | 530 | 90 |
| | + | FP | WW | GM | SF | | | 12% | 551 | 81 |
| | + | WW | SF | FP | GM | | | 12% | 533 | 79 |
| BG, BG 32 | - | WOR | WW | SF | GM | | | 14% | 628 | 103 |
| | + | SY | WW | SF | WW | | | 22% | 631 | 77 |
| BG, BG 33 | - | WOR | WW | SF | GM | | | 13% | 628 | 102 |
| | + | CB | WW | SF | WW | | | 20% | 481 | 64 |
| RO, RO 11 | - | GM | WW | | | | | 29% | 545 | 97 |
| | | GM | WW | SY | | | | 29% | 615 | 82 |
| RO, RO 21 | - | GM | SF | WW | | | | 13% | 613 | 108 |
| | + | GM | WW | SY | | | | 14% | 879 | 114 |
| RS, RS 12 | - | GM | WW | | | | | 15% | 636 | 108 |
| | + | GM | WW | SY | | | | 17% | 1000 | 117 |
| UA, Kyiv oblast | - | GM | SF | WW | | | | 13% | 657 | 114 |
| | + | GM | SY | SF | WW | | | 14% | 763 | 102 |
| **Central-western Europe** | | | | | | | | | | |
| AT, AT 11 | - | GM | GM | WW | | | | 6% | 849 | 154 |
| | + | SY | WW | GM | | | | 12% | 1057 | 124 |
| AT, AT 12 | - | GM | WW | SF | | | | 19% | 557 | 97 |
| | + | GM | WW | SY | | | | 19% | 776 | 94 |
| DE, DE 11 | - | WW | WB | TR | | | | 13% | 794 | 120 |
| | + | WW | WB | FP | TR | | | 11% | 770 | 105 |
| DE, DE 11 | - | SU | WW | WB | GM | | | 13% | 979 | 180 |
| | + | SU | WW | WB | FB | | | 12% | 977 | 153 |
| DE, DE 13 (gravel) | - | GM | GM | WW | WOR | | | 12% | 788 | 137 |
| | + | GM | GM | SY | WW | WOR | | 12% | 847 | 123 |
| DE, DE 13 (silt) | - | GM | GM | WW | WOR | | | 12% | 960 | 168 |
| | + | GM | GM | SY | WW | WOR | | 12% | 1038 | 150 |
| DE, DE 40 (soil type 2) | - | WW | WB | WOR | | | | 20% | 663 | 97 |
| | + | WW | FP | WW | WB | WOR | | 19% | 681 | 84 |
| | + | WW | SY | WW | WB | WOR | | 22% | 745 | 92 |
| DE, DE 40 (soil type 3) | - | WR | WR | WOR | | | | 20% | 531 | 86 |
| | + | WR | FP | WR | WOR | | | 20% | 559 | 79 |
| | + | WR | L | WR | WOR | | | 25% | 584 | 79 |
| DE, DE 73 | - | WOR | WW | WW | SB | | | 12% | 711 | 118 |
| | + | WOR | WW | FP | WW | SB | | 13% | 753 | 109 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 18. Production-related impact assessment of reference and legume-supported arable cropping systems in case study regions in north-western and southern Europe

| Region | +/- legume | C1 | C2 | C3 | C4 | C5 | C6 | Yield stability (CV) | Protein output [kg/ha] | Energy output [GJ/ha] |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Arable cropping systems*** | | | | | | | | | | |
| **North-western Europe** | | | | | | | | | | |
| GB, UKM 7 | - | WOR | WB | WO | SB | WB | | 7% | 707 | 111 |
| | + | WOR | WB | WO | FP | WB | | 8% | 775 | 108 |
| | + | WOR | WB | WO | FB | SB | | 9% | 820 | 105 |
| IE, IE 05, IE, 06 | - | WB | WO | WW | WB | WOR | WW | 14% | 1097 | 148 |
| | + | WB | WO | WW | FB | WW | | 13% | 1241 | 145 |
| IE, IE 05, IE, 06 | - | SMB | SO | SFB | SMB | SMB | | 13% | 761 | 116 |
| | + | SMB | FB | SO | SFB | SMB | | 13% | 930 | 112 |
| **Southern Europe** | | | | | | | | | | |
| IT, ITH 4 | - | GM | GM | GM | | | | 16% | 990 | 197 |
| | + | GM | SY | | | | | 20% | 1338 | 158 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

Table 19. Production-related impact assessment of reference and legume-supported forage cropping systems in case study regions in central-western and north-western Europe

| Region | +/- legume | C1 | C2 | C3 | C4 | C5 | C6 | Yield stability (CV) | Protein output [kg/ha] | Energy output [GJ/ha] |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Forage cropping systems*** | | | | | | | | | | |
| **Central-western Europe** | | | | | | | | | | |
| DE, DE 40 | - | WW | WR | SM | SM | SM | | 16% | 801 | 158 |
| | + | WW | WR | AF | AF | AF | | 17% | 1245 | 138 |
| **North-western Europe** | | | | | | | | | | |
| GB, UKM 9 | - | GR | GR | GR | SB | | | - | 1781 | 217 |
| | + | GC | GC | GC | WW | | | - | 1960 | 228 |
| | + | GC | GC | GC | SB | FP/SB | WW | - | 1650 | 202 |
| | + | GC | GC | GC | SB | FP | WW | - | 1690 | 202 |
| | + | GC | GC | GC | SB | FB | WW | - | 1695 | 193 |
| | + | AF | AF | AF | SB | | | - | 1543 | 154 |
| | + | WW | GC | GC | GC | SB | | - | 1731 | 211 |

AF, Alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.