Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: A review

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Grain legume production offers multiple environmental benefits and can enhance sustainability of European farming, but their production area is declining constantly. Grain legume competitiveness is frequently constrained by lower gross margins compared to agronomically suitable cropping alternatives, but it can be improved by appreciating their ability to increase yield of subsequent crop(s) and, potentially, to reduce input requirements (fertiliser, biocide, tillage). Information on the magnitude of grain legume pre-crop effects is diverse and has not been synthesised for European agriculture. This paper reviews research on pre-crop benefits to yield and input requirements of subsequent crops, and the farm-economic profitability of grain legumes in European cropping systems. This includes an analysis of the magnitude of pre-crop benefits to cereal yields measured in 29 experiments in Europe; and 19 studies on grain legume gross margins ranging from crop to cropping system level are assessed. In the available studies, yield benefits of legumes to subsequent crops are highest under low nitrogen fertilisation to subsequent crops and fertilisation can be reduced by 60 kg N ha\textsuperscript{-1} on average under maintenance of acceptable yields. With the aim at maximising yield potential, nitrogen fertilisation following grain legumes can be reduced by 23–31 kg ha\textsuperscript{-1}, and cereal yields are mostly 0.5–1.6 Mg ha\textsuperscript{-1} higher than after cereal pre-crops. With adequate estimates of pre-crop benefits, gross margins of full crop rotations can better assess grain legume competitiveness. In the studies reviewed, 35 of 53 modelled crop rotations with grain legumes were competitive with comparable non-legume rotations. Grain legume rotations were more competitive under conservation tillage systems if gross margin calculations accounted for cost savings arising from adjusted machinery requirements. In conclusion, grain legume pre-crop value is a crucial component of their farm-economic profitability in European cropping systems, but further experimental research is required to ascertain its magnitude. Expanding profitability measures to consider pre-crop effects substantially increases the number of situations where grain legumes can compete with cereals, and has a small positive effect on their competitiveness with alternative break crops. Besides a better consideration of the pre-crop value, further genetic and agronomic improvement in legume cropping, supportive market development, and policy support are required if Europe is to utilise environmental benefits of legumes and increase the sustainability of its farming.

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\textbf{Abbreviations:} N, nitrogen; GM, gross margin; FNE, fertiliser nitrogen equivalent.

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0378-4290© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
1. Introduction

Grain legume cultivation provides multiple environmental benefits to agricultural landscapes in Europe, increases resource efficiency, and contributes to balancing Europe’s deficit in plant protein production (Smil, 2002; van der Werf et al., 2005; Nemec et al., 2008; Peoples et al., 2009b; Jensen et al., 2010; Köpke and Nemec, 2010; Westhoek et al., 2011). Yet, farmers’ cropping decisions rarely favour legume production in Europe, leading to its constant decline in most of the EU. From 1961 to 2013, areas declined from 5.8 to 1.8 million ha, which corresponds to 4.7 to 1.7% of the EU-27 arable area (based on FAOstat, 2014). This reduction in legume production is part of a deeper land use change in Europe towards more specialised and intensive production, especially of cereals and oil crops (Supit, 1997; Brouwer, 2006; Omer et al., 2007; Pascual and Perrings, 2007). Market forces stimulate specialisation of cropping systems, as non-marketed benefits of diversification, like legume farming, do not contribute to profits (Zander et al., unpublished). In spite of this global agricultural trend, the European decline in legume production contrasts the developing grain legume sectors in other regions, e.g. in Canada or Australia (Schilizzi and Kingwell, 1999; Zentner et al., 2002). As farmers ultimately decide whether to grow grain legumes, policies have to address the agronomic benefits and farm-economic attractiveness of grain legumes.

To assess the farm-economic value of grain legumes, their contribution to subsequent crops in the cropping systems (pre-crop effect) need to be taken into account (Beattie et al., 1974; Weithbrecht and Pahl, 2000; LMC International, 2009b). The role of grain legumes in cropping systems is increasingly well understood with respect to N fixation, mechanisms of pre-crop effects, and environmental impacts (Chalk, 1998; Nemec et al., 2008; Peoples et al., 2009a; Köpke and Nemec, 2010; Jensen et al., 2011) and their potential in organic farming, conservation tillage or northern margins of crop production has been pointed out (Robson et al., 2002; Luettek-Enstrup et al., 2006; Peltonen-Sainio and Niemi, 2012). Schilizzi and Pannell (2001) and Beattie et al. (1974) have conceptualised the farm-economic valuation of the rotational benefits of legumes. A legume crop’s pre-crop effect can be considered as a by-product and valued using a shadow price that equals the marginal value productivity of the subsequent crop (Beattie et al., 1974). Consequently, Schilizzi and Pannell (2001) point out that this pre-crop value is situation-specific and represents a private value of the pre-crop effect for the specific farm and agronomic situation. They describe how optimal levels of production and input allocation can be calculated when magnitude and economic value of pre-crop effects are known.

However, information on the magnitude of grain legume pre-crop effects is diverse and specific to sites and farming systems and has not been synthesised for European agriculture, in contrast to detailed studies on yield benefits in Australia and Northern America (Angus et al., 1991; Evans et al., 1991; Chalk, 1998; Seymour et al., 2012; Zentner et al., 2002), a review for tropical systems (Peoples and Craswell, 1992), and on farm-economic benefits in Canadian cropping systems (Zentner et al., 2002). Kirkegaard et al. (2008) have included but not separately analysed grain legumes in the quantification of break crop benefits in European experiments. In Europe, pre-crop benefits may differ from those regions due to Europe’s overall higher yield levels and different economic conditions. Knowledge on the magnitude of pre-crop benefits specifically in the European context is required to understand the farm-economic competitiveness of grain legumes. This enables informed decisions on agricultural landscape management with the aim of utilising environmental benefits of legumes and increasing the sustainability of European farming.

This paper aims to review research on pre-crop benefits and farm-economic profitability of grain legumes in European cropping systems, and integrate knowledge gained from plant science on pre-crop effects with economic analyses. To do so, we pursue two objectives: (1) analyse and quantify benefits of grain legumes to the cropping system shown in European experiments; and (2) review economic assessments of grain legumes based on crop gross margins (GM) and alternative methods for gross margin calculation that include cropping system benefits. As the objective of this paper is to understand grain legume profitability independent of policy influences, criteria and benefits that are not economically valued (e.g. biodiversity, climate change mitigation potential) are not in the scope of this review even if they might be rewarded by existing or possible future policy schemes. Similarly, the role of grain legumes in intercropping or in organic agriculture is out of the scope of this paper.
2. Materials and methods

2.1. Literature retrieval

Aiming at a near-exhaustive review, literature databases (Scopus, Web of Knowledge) were searched for the terms “legume”, “protein crop” and the English and scientific names of different grain legume crops in combination with the terms “previous crop”, “preceding crop”, “pre-crop”, “break crop”, “rotation”, “economic”, and “profitability”. The search was further broadened by checking relevant references of the literature obtained. Similarly, grey literature was searched to increase coverage and reduce publication bias with respect to reported pre-crop benefits. The same keywords and their respective translations in German or French language were searched for in Google scholar, conference proceedings (e.g. ESA, LCA Food) and websites of relevant organisations (UFOP, UNIP, regional agricultural research institutes).

2.2. Yield effect synthesis

2.2.1. Inclusion criteria and description of studies

For quantification of yield benefits, references were required to report replicated field trials on the effect of grain legumes and a reference pre-crop on the yield of subsequent cereals or rapeseed. They had to allow for a pair-wise comparison of legume to non-legume pre-crops, and report level of nitrogen (N) fertilisation to the pre-crops and subsequent crops. In total 29 references fulfilled these specific requirements. Another 25 retrieved references were excluded because they (a) did not report field experiments but model results, pot experiments or statistical data from practice (5 references), (b) reported pre-crop effects of legumes grown for forage (6 references), (c) did not allow for pairwise comparison of legume to non-legume pre-crops (4 references), (d) reported yield benefits to crops other than cereals or rapeseed (5 references), or (f) did not specify important experimental data, especially replications, N level, or absolute yield values (5 references).

For the data included, absolute (in Mg ha\(^{-1}\)) and relative (in %) yield benefits of grain legumes to subsequent crops were calculated in comparison to several reference pre-crops. Different crop comparisons, N levels, and sites within experiments were included as individual observations, whereas they were averaged over years and other treatments, where applicable (e.g. tillage system, crop varieties, type and timing of fertilisation) in order to avoid a bias towards longer or larger experiments. Data for rare treatments such as irrigation, underseeds, intercrops, or crops not normally grown in a specific site were excluded.

Details on the 29 studies included in the synthesis analysis are given in the annex (Table A.1). Fifteen experiments were laid out in blocks and six were fully randomised, plots were whole plots in three, split-plots in 15 and split-split-plots in another three experiments; seven did not report exact experimental design. Experiments included up to 20 years of test-crops and up to four sites. They included eight studies not published in peer-reviewed journals (research reports, PhD theses, results presented in monographs, applied science journals). Seven experiments were conducted before 1990 and should be interpreted carefully. Breeding progress may have affected pre-crop benefits since that time, e.g. due to less crop residues from leafless pea varieties or increased lodging resistance in subsequent cereals enabling high N uptake. However, the studies did not produce atypical observations compared with more recent experiments and were therefore included.

2.2.2. Grouping and presentation of data

Experiments were grouped into temperate and Mediterranean climatic regions. Nine experiments originated from Mediterranean climates, thereof seven from Spain and one each from Cyprus and Italy. They tested the grain legumes chickpea, faba bean, vetch and pea (in 6, 5, 3, and 1 experiment, respectively) as pre-crops to the cereals wheat, durum wheat, and barley (4, 2, and 3 experiments, respectively). Reference pre-crops were grouped to cereals (barley, wheat, durum wheat, 8 experiments), sunflower as a broad-leaved pre-crop (6 experiments), as well as previous fallow (5 experiments). A distinction of pre-crop effect by N fertilisation level was not possible due to insufficient references reporting pre-crop- and fertilisation-specific yield.

Twenty experiments originated from temperate climates, thereof twelve from Germany, four from the UK, two from Denmark and each one from Austria and Switzerland. They tested the grain legumes pea, faba bean, and lupin (in 15, 14 and 4 experiments, respectively) as pre-crops to the cereals wheat, barley, rye, and oats (in 16, 4, 2, and 1 experiment, respectively). Pre-crop benefits to subsequent rapeseed were also tested in four of these experiments and were considered separately. For the effects on cereals, reference pre-crops were grouped to cereals (barley, wheat and rye, 14 experiments), oats as a reference crop with intermediate pre-crop characteristics between cereals and broad-leaved crops (11 experiments) and broad-leaved pre-crops (rapeseed, sugar- and fodder beets, linseed, 9 experiments). Reference pre-crops used in few other experiments or with incomplete time-series in experiments were excluded (e.g. potato, sunflower, maize). To distinguish among levels of fertilisation to subsequent crops, N fertiliser treatments were grouped into no N fertilisation (0 kg ha\(^{-1}\)), moderate N fertilisation (20–90 kg ha\(^{-1}\)), and high N fertilisation (above 100 kg ha\(^{-1}\)). Where several treatments in one experiment fell into one category, these treatments were averaged to obtain one value per N level and experiment.

Data of the included experiments were synthesised and presented in box plots, as a graphical presentation and exploratory tool used in meta-analysis (Greenhouse and Iyengar, 2009). In the papers analysed, standard errors for pre-crop specific yields were not always reported so no attempt was made to combine results into a statistically verifiable average effect. Alternatively, the inner quartile range of these plots, which is considered a robust measure of variability (ibid.), was chosen to provide a range of effect sizes that are probable estimates in a typical situation.

2.3. Economic assessment and terms employed

For an economic assessment of grain legumes, included literature was required to (a) report gross margin (GM) of grain legumes in Europe in comparison to another reference crop, (b) clearly present the method of GM calculation, yield, price, subsidies and variable costs included, and (c) where applicable, present the nature and size of pre-crop benefits considered. Of 20 studies in total, 19 reported grain legume GM compared to other crops, their GM figures were recalculated so as to exclude subsidies, where necessary, to assess grain legume competitiveness independent from policy influences that vary between sites and years. Since prices, however, do vary between years and countries, absolute GMs for different case studies from different publications cannot be compared directly, rather the relative performance of grain legumes over other crops is compared. Furthermore, three studies reporting variation in grain legume yield and GM were compiled.

We distinguish GMs at the scale of single crops (6 studies) or at the scale of crop sequence (5 studies), crop rotation (7 studies), and cropping system (1 study). By crop sequence we describe a temporal sequence of two to three crops grown consecutively. A crop rotation describes a fixed cyclical crop sequence of often at least three years, specifically designed to balance different agronomic characteristics of the crops included. A cropping system describes a combination of crop rotations, a specific tillage system and input intensity.
GM is the appropriate measure for assessing and comparing crop enterprises in farm business management (defra, 2010). Given the benefits of grain legumes to cropping systems described below, crop level GM may not be an adequate indicator for grain legume competitiveness. Therefore, different authors have argued for alternative calculation methods of grain legume GM that are expanded to encompass cropping system benefits. We present several forms of GM according to the different scales for assessing crop enterprises.

At the scale of single crops, the crop gross margin (GM) equals its market value:

\[ GM = Y \times P - C_{dir \, var} \]  \hspace{1cm} (1)

where \( Y \) is the crop yield and \( P \) its price. \( C_{dir \, var} \) are the direct variable costs of production, which include costs for fertilisers and soil improvement, crop protection, seed and seedlings, and other crop costs such as for off-farm storage and market preparation, insurance, and interest, but they exclude any costs for labour and machinery (definition European farm accountancy data network FADN, Barkaszi et al., 2009). However, GM may be applied differently and some authors include variable labour and machinery costs such as for contract work, fuel and proportional depreciation, this is explicitly noted where applicable. To include grain legume’s contributions to crop sequences, expanded GMs (GM\(_{exp}\)) have been calculated (e.g. Weitbrecht and Pahl, 2000; Alpmann et al., 2013b), that sum up a crop’s market and precrop values; it equals:

\[ GM_{exp} = GM + (Y_{B_{sub}} \times P_{sub} + C_{S_{sub}}) \]  \hspace{1cm} (2)

where \( Y_{B_{sub}} \) is the yield benefit (additional yield), \( P_{sub} \) the price and \( C_{S_{sub}} \) the cost savings of the subsequent crop, the term in brackets forms the ‘pre-crop value’. For assessment at the rotation scale, a rotation GM (GM\(_{rot}\)) can be calculated (e.g. von Richthofen et al., 2006b), to reflect a crop’s effect on the design of the rotation, including all crops, cover crops and fallow periods:

\[ GM_{rot} = \sum_{crop \, 1-i} GM \]  \hspace{1cm} (3)

\( i \) is the number of the respective crops in the rotation. The measure is averaged over the number of years to obtain a comparable annual measure. Where GM\(_{exp}\) are modelled, yields and input costs have to be adjusted specific to the respective pre-crops.

To reflect legumes’ farm-level economic effects that arise from reduced labour and machinery requirements, profit, net margins (defra, 2010), and semi-net margins (Lechenet et al., 2014) are applied in studies on tillage systems (e.g. Sánchez-Girón et al., 2004, 2007), but none comparing crops or rotations using these measures were found. To account for effects on machinery requirements, the use of external inputs and accompanying changes of cropping pattern and seed supply, assessments at farm level have been proposed (Schilizzi and Pannell, 2001). Luetke-Entrup et al. (2006) proposed an intermediate measure that does not require calculating costs unaffected by cropping systems, such as land and miscellaneous overhead costs. They defined the DAL margin (GM\(_{DAL}\)), which can be described as rotation GM less any labour and machinery costs:

\[ GM_{DAL} = \sum_{crop \, 1-i} (GM - C_{mach \, lab}) \]  \hspace{1cm} (4)

where \( C_{mach \, lab} \) is the fixed and variable costs for machinery, labour, implements and services, including depreciation, insurance, interest, storage (fixed costs) and fuel, maintenance costs as well as costs of contract work (variable costs per operational hours and ha). These costs are governed by the machinery endowment, i.e. the number, size and type of machinery and implements owned by the farm. It is modelled by least-cost machinery selections (e.g. Sánchez-Girón et al., 2004, 2007), or a machinery selection required to efficiently use available labour in peak labour times (Luetke-Entrup et al., 2006), for model farm enterprises with defined acreage, tillage system, and crop rotation.

3. Magnitude of grain legume benefits to the cropping system

In this section, we first describe the pre-crop benefits of grain legumes and then concentrate on their farm-economically most relevant aspects: the magnitude and economic balance between yield benefits and fertiliser savings and the supporting role of grain legumes in reduced tillage farming.

3.1. Cropping system benefits

Grain legumes improve growing conditions and increase the yield of subsequent crops in the rotation, an effect that has been analysed in several reviews (Jensen, 1997; Chalk, 1998; Luetke-Entrup et al., 2003a; Giambalvo et al., 2004; Kirkegaard et al., 2008; Peoples et al., 2009a,b; Köpke and Nemecek, 2010). Fig. 1 summarises the farm-economically relevant pre-crop effects that increase GMs of subsequent crops.

The agronomic pre-crop benefits of grain legumes (Fig. 1(a)) encompass two components (Chalk, 1998): The so-called ‘nitrogen effect’ is caused by N provision from biological fixation and N sparing processes that provide a longer-term supply to other crops (Peoples et al., 2009a). The ‘break crop effect’ includes benefits to soil organic matter and structure (e.g. Leithold et al., 1997; West and Post, 2002; Wu et al., 2003; Herranz et al., 2009), phosphorus mobilisation (Egle et al., 2003; Shen et al., 2011), and reduced pressure from diseases and weeds (e.g. Robson et al., 2002). Benefits derived from N provision are highest in situations of low N fertilisation, and benefits from ‘break crop effects’ are highest in cereal-dominated rotations, where disease reduction can be one of the most important yield benefitting factors of grain legumes (Prew and Dyke, 1979; McEwen et al., 1989; Stevenson and van Kessel, 1997). Besides grain legumes, many broad-leaved crops or summer cereals lead to similar rotational benefits, therefore cereals following different ‘break’ crops are reported to yield on average 24% more than cereals grown continuously in Northern Europe (Kirkegaard et al., 2008).

The individual benefits enable potential cost savings (Fig. 1(b)) in the subsequent crop (Luetke-Entrup et al., 2006; von Richthofen et al., 2006b; Jensen et al., 2010) and support reduced or zero tillage systems, where non-mechanical soil loosening and disease and weed management is crucial (Zentner et al., 2002; Sánchez-Girón et al., 2004, 2007; Luetke-Entrup et al., 2006; Ozpinar and Ozpinar, 2011).

The combination of agronomic effects increases revenue (Fig. 1(c)) through increased yields and in many cases improved quality parameters like grain N and protein content and protein yield in cereals after legumes (e.g. Könnecke, 1967; McEwen et al., 1989; dos Santos et al., 1993; Wivistad et al., 1996; López-Bellido et al., 1998, 2001; Galantini et al., 2000; Albrecht and Gudat, 2004; Papastylianou, 2004). However, the quality effect varies with management factors, is not consistent (Prew and Dyke, 1979), and often remains below economic relevance. Yield benefits are obviously interdependent with potential fertiliser savings and highest when compared to unfavourable pre-crops (pure cereal sequences). For example, Angus et al. (2001) collated yield benefits compared to pure cereal sequences in Australia of 40–50% for low N levels and 10–17% for high N levels, however Seymour et al. (2012) found that in experiments conducted after 1990, benefits remained constant from zero to above 50 kg N ha\(^{-1}\). Therefore, an economic balance of the trade-off between N fertilisation and yield potential is required (Fig. 1(d)). Although grain legume pre-crops enable
acceptable yields of subsequent crops under reduced fertilisation, highest yields are still achieved when fertilisation is not reduced. Schilizzi and Pannell (2001) developed an algorithm for optimising this economic balance, i.e. the extent of utilising N from grain legumes when magnitude and economic value of pre-crop effects are known. However, these “…cannot be defined in absolute terms but will always depend on how it fits into the farming system" (Schilizzi and Pannell, 2001).

3.2. Yield benefit as affected by N intensity

Numerous experimental data highlight the yield benefits of legumes to subsequent cereals and rapeseed in temperate and Mediterranean Europe. Fig. 2 compiles the average yield benefits found in these experiments, and detailed results are available as supplementary data (Table A.2). The wide range of measured yield benefits provides little orientation, whereas median values alone are not representative for a range of environments. Therefore, the inner quartile range of yield benefits, i.e. the box length in Fig. 2, is considered as a range of probable estimates for a typical situation and used to summarise experimental results.

We consider three possible strategies to balance the trade-off between N fertiliser savings and yield benefits, ranging from cost minimisation to yield maximisation:

(a) No fertiliser application to subsequent crops with the aim to determine theoretic yield benefit potential of grain legume pre-crops.
(b) Moderate fertilisation to subsequent crops with the aim to maximise fertiliser savings potential; i.e. fertilisation is reduced to the degree that supports an acceptable yield similar to that after non-legume pre-crops.
(c) High fertilisation to subsequent crops with two possible aims:
   Avoid fertiliser adjustments or find an economic balance between fertiliser savings and yield potential.

With regard to (c), avoiding fertiliser adjustments is most profitable where fertiliser costs are very low relative to product prices and fertiliser adjustments would lead to significant transaction costs. This is especially the case for farms with abundant or even excess N available from animal manure (see Westhoek et al., 2011), and when a farmer would need to buy a special type of mineral fertiliser to maintain the optimum levels of all other nutrients (Reckling et al., 2014). Balancing fertiliser reduction and yield potential at low N fertiliser prices relative to product prices translates into only minimal fertiliser savings while achieving high yields, even if the full potential environmental and resource benefits of grain legumes are not realised. Schilizzi and Pannell (2001) found for Australian farming systems that with lower fertiliser-N to product-price ratios yield benefits of legumes “are worth more to farmers than their N fixation capacity”.

3.2.1. No fertiliser application to subsequent crops

The yield benefit of grain legumes to subsequent unfertilised crops, according to strategy (a), shows the full potential of grain legume pre-crops to increase yields of subsequent crops (Fig. 2A), with consistent yield benefits in all experiments. However, this strategy is of less practical relevance as the yield of unfertilised cereals after grain legumes is still far below that of cereals receiving moderate or usual fertiliser levels. Compared to other broad-leaved pre-crops in temperate regions, cereals following grain legumes yield mostly 0.5–1.8 Mg ha\(^{-1}\) more (increase by 11–41%). Compared to oats or cereal pre-crops, the benefits are higher and more variable with 0.9–2.8 Mg ha\(^{-1}\) (increase by 27–110%).

3.2.2. Maximising potential for N fertiliser savings

Reducing fertiliser levels as far as possible while maintaining yields (strategy b) is feasible when fertiliser costs relative to product prices are high or there are limitations on fertiliser use, e.g. in organic farming or other environmental schemes (Agri-Environment Schemes, water protection areas, agriculture within protected areas). Also in systems where other factors than nutrients constrain yields, e.g. low precipitation in drier Mediterranean climates, this strategy may be suitable due to a low yield response to higher N levels; in those cases the cost-efficiency ratio of legume-N over yield benefits would be high. When fertilisation to subsequent cereals is reduced to moderate levels of N fertiliser (experiments with 20–90 kg ha\(^{-1}\) N fertilisation), yield benefits of grain legumes to cereals are small on average compared to other broad-leaved pre-crops, with mostly 0.1–0.4 Mg ha\(^{-1}\) extra yield (increase by 2–12%, Fig. 2A), and three experiments observed no or negative effects. The benefit is higher and almost consistent (one negative observation) in comparison to oats, with 0.3–0.7 Mg ha\(^{-1}\) extra yield (increase by 8–17%), and highest and consistently positive in comparison to cereals, with 0.5–1.2 Mg ha\(^{-1}\) extra yield (increase by 12–25%).

The highest potential N fertiliser savings under this strategy (Table 1A) can be described as the fertiliser nitrogen equivalent
Fig. 2. Yield benefits (Mg ha\(^{-1}\)) of grain legume pre-crops to subsequent crops in European experiments, for individual data see annex (Table A.2). Vertical line in boxes denotes median, boxes drawn from 1st to 3rd quartile, box length indicates inner quartile range (IQR), \(\dagger\) whiskers range of data distribution, \(\times\) marks represent outliers that are located a distance more than 1.5 times the IQR from the nearest quartile.

(1) Inner quartile range is the range from the 1st to the 3rd quartile and is considered a probable estimate for a typical situation.
(2) According to Greenhouse and Iyengar (2009).
(3) Insufficient data available to distinguish between N rates or compared crops.


Table 1
Economic amounts of N fertiliser savings in cereals following grain legumes compared to pure cereal sequences under different strategies for utilising pre-crop benefits.

<table>
<thead>
<tr>
<th>Estimate</th>
<th>N savings (kg ha(^{-1}))</th>
<th>Sources: countries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>(A) Best utilising N fertiliser savings potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertiliser nitrogen equivalent</td>
<td>62 kg</td>
<td>35–108 kg</td>
</tr>
<tr>
<td>(B) Best utilising yield potential</td>
<td>23 kg</td>
<td>0–50 kg</td>
</tr>
<tr>
<td>Producer practice (survey results)</td>
<td>27 kg</td>
<td>20–30 kg</td>
</tr>
<tr>
<td>Additional N take-up (experimental results)</td>
<td>15–57 kg</td>
<td></td>
</tr>
<tr>
<td>Reduced crop N requirements for optimum yield (model results)</td>
<td>23 kg</td>
<td>0–40 kg</td>
</tr>
</tbody>
</table>
(FNE), which is the fertiliser reduction that leads to yields comparable to those after a cereal pre-crop. Notably, this yield is still lower than the potential yield with full fertilisation and legume pre-crop, i.e. a certain trade-off between fertiliser savings and yield occurs. Depending on the main and the pre-crop, the FNE can attain on average 62 kg ha\(^{-1}\) for subsequent cereals in Europe, which is lower than North American estimates with 75 and 120 kg ha\(^{-1}\) (Wright, 1990; Badaruddin and Meyer, 1994), but comparable to estimates from Australia and tropical systems with 40–80 kg ha\(^{-1}\) (Hamblin, 1987; Doyle et al., 1988), and 12–68 kg ha\(^{-1}\) (Peoples and Craswell, 1992), respectively.

3.2.3. Maximising yield potential

With usual or high fertilisation (100–200 kg N ha\(^{-1}\)), cereal yields when preceded by grain legumes are comparable to those after other broad-leaved pre-crops (≥0.3 Mg ha\(^{-1}\), Fig. 2A) with a similar number of positive and negative observations. However, they are often slightly higher than when using oats as pre-crop with −0.1 to 0.4 Mg ha\(^{-1}\) extra yield (increase by −2 to 6%) and substantially and consistently higher than after cereals, with 0.5–1.6 Mg ha\(^{-1}\) extra yield (increase by 5–25%). Analyses of cereal yield statistics in Germany and France quantified yield benefits of grain legumes to wheat achieved in practice between 0.5 and 1.2 Mg ha\(^{-1}\) compared to cereal pre-crops (Steinbrenner, 1990; Michel et al., 2007; Brisson et al., 2010), which fit the range of experimental results under moderate and high fertilisation.

Table 1B compiles different estimates of N fertiliser savings that support maximum yields; it includes expert estimations and farmer practice as an indicator of farm-economic valuations, as well as modelled and experimentally measured estimations. Similarly across different estimates, economic N savings for maximum yields average 23–31 kg ha\(^{-1}\), and enable average cost savings of 18–24 € ha\(^{-1}\) (2012 ureda price averaged over several countries, Eurostat, 2014). This figure for Europe is comparable to the estimates of 12–55 kg ha\(^{-1}\) reported from America or Australia (Wright and Coxworth, 1987 in Badaruddin and Meyer, 1994; Evans et al., 2003). However, the range of N savings includes low values, i.e. situations where very low reduction in N fertilisation is agronomically and economically feasible: in situations with high leaching losses of legume-provided N (Albrecht and Guddat, 2004), in sites with generally low N input (von Richthofen et al., 2006b), or where fertiliser adjustments are avoided (see Section 3.1). Consequently, when a farmer reduces fertilisation after the legume by the average amount, yield losses may still occur in some years or sites, but regularly measuring N savings potential may not be feasible in practical farming. Faba bean produces higher N benefits to subsequent crops than pea (McEwen et al., 1989; Maidl et al., 1996). The scale of fertiliser reduction depends on subsequent crops as well, i.e. the potential for N fertiliser saving reduces in the order wheat > rapeseed > rye > maize (Charles and Vuilloud, 2001).

3.3. Yield benefit not distinguished by N intensity

Grain legumes were also shown to substantially and consistently benefit subsequent rapeseed in temperate sites, with mostly 0.4–0.7 Mg ha\(^{-1}\) extra yield (increase by 9–20%, Fig. 2B). Rapeseed often reacted with higher yield increases than cereals did within the same experiments (not shown). Rapeseed has a high potential to utilise autumn-mineralised N and can still achieve around 0.5 Mg ha\(^{-1}\) extra yield after grain legumes even at higher fertilisation.

In Mediterranean sites (Fig. 2C), cereals after grain legumes yielded mostly 0.2–1.5 Mg ha\(^{-1}\) more when compared to the yields obtained after cereals or sunflower (increase by 9–79%), but effects were not consistently positive. On the one hand, absolute yield benefits may be smaller in Mediterranean sites because factors not influenced by legumes constrain maximum yield levels, especially water availability, but relative yield increases are still large considering the overall lower yield levels. When fertilised with 80 kg N ha\(^{-1}\) or more, yield benefits remained minimal especially in comparison to rapeseed or sunflower (not shown). This may be explained by the low response of wheat to N levels above 100 kg ha\(^{-1}\) in dry climates (López-Bellido et al., 2012). Compared to a preceding fallow, cereals yielded up to 1 Mg ha\(^{-1}\) less when preceded by grain legumes, due to the positive effect of water conservation during fallow periods.

3.4. Scale and variation of yield benefits

The absolute size of yield benefits of grain legumes compared to cereal pre-crops in Europe reported as inner quartile ranges (extra yield, Fig. 2) is comparable to that reported from other regions, whereas relative figures (percentage yield increase) are considerably lower. In reviews covering a broad range of site-years, Evans et al. (1991) reported yield increases of subsequent cereals of 0.7 and 0.9 Mg ha\(^{-1}\) (32 and 44%) for lupin and pea, respectively, and Seymour et al. (2012) an increase by 0.6 and 0.45 Mg ha\(^{-1}\) for the same crops. Similarly, Peoples and Craswell (1992) report a range of 0.3–1.6 Mg ha\(^{-1}\) (10–98%) for different grain legume crops to wheat in tropical farming systems. This discrepancy between absolute and relative benefits can be explained by the higher reference yields in Europe and possibly by a large influence of experiments with no or comparably small fertiliser application in other reviews. It also supports the observation that yield benefits of grain legumes are of a comparatively constant absolute size, rather than a proportional increase in yield (Seymour et al., 2012).

The yield benefits show large variation in experimental results (Fig. 2), altogether ranging from −0.2 to +3.1 Mg ha\(^{-1}\) extra yield (−11 to +156% of the reference yield) for temperate sites and from −2.1 to +3.0 Mg ha\(^{-1}\) extra yield (−44 to 265% of the reference yield) for Mediterranean sites. This large variation can only partly be accounted for by distinguishing fertilisation strategy and reference pre-crop. Similarly large variability has been reported by Seymour et al. (2012) for lupin pre-crops in Australia, and could partly be explained by regional differences, an increase in pre-crop benefits with better lupin yields, as well as change in agronomic practices towards no-till. Climatic conditions greatly influence the size of the pre-crop effect and determine when pre-crop benefits of grain legumes take effect and if they last more than one season. Under dry Mediterranean climatic conditions, variability in rainfall was illustrated as an important cause for the variation in pre-crop benefits by López-Bellido et al. (2012, 2013). Yield limiting dry conditions cause low yield benefit of legumes in dry years, and N accumulation limits benefits in the next year with normal precipitation as well. This may explain insignificant yield benefits found by Sánchez-Girón et al. (2004) as well as a high carry-over of the pre-crop effect to the second subsequent crop found by Papastylianou (2004). Conversely, low mineralisation under conditions of low temperatures may have delayed the pre-crop effect to the second subsequent crop in a Finnish experiment (Keskitalo et al., 2012). Under temperate climatic conditions, the second subsequent crop after grain legumes benefited with about 400–500 kg ha\(^{-1}\) extra yield in some experiments (Steinbrenner, 1990; Köpke, 1996; Charles and Vuilloud, 2001; Albrecht and Guddat, 2004), but insignificant effects of less than 100 kg ha\(^{-1}\) were also often observed (Könnecke, 1967; Prew and Dyke, 1979; Panse et al., 1994; Maidl et al., 1996; Dachler and Köchl, 2003).

When comparing grain legumes, lupins produce generally highest yield benefits, followed by faba bean, whereas pea and vetch produce lower ones (see also Hatch et al., 2010), but these differences may be confounded with site differences where the respective legumes are grown. The compiled studies have not tested the
pre-crop effect of soya bean in European conditions, which may be small or even negative according to North American research due to their mostly negative N balance and less benefits to soil structure (Paré et al., 1992, 1993; dos Santos et al., 1993; Mays et al., 1998).

3.5. Benefits to soil tillage reduction and labour and machinery requirements

Grain legume benefits to soil properties and pest and disease pressure (see Section 3.1) and their small amount of residues facilitating seed bed preparation (Luette-Entrup et al., 2006; Hernandez et al., 2009) can be utilised in three possible ways with increasing cost and energy savings: (a) time and fuel requirements of standard tillage operations following the legume are reduced (Könnecke, 1967), (b) tillage is omitted following the legume, or (c) conservation tillage is applied on the whole farm, facilitated by a legume rotation. Of 75 grain legume producers surveyed in Germany, 35 respondents stated they applied zero tillage after a legume pre-crop, and another 30 applied reduced tillage on the whole farm (Schäfer et al., 2013). These tillage reductions immediately reduce costs for maintenance, fuel and depreciation of machinery and implements. Von Richthofen et al. (2006b) estimated that unploughed cultivation of wheat following pea or rapeseeds saves 30–40 € ha⁻¹ and 100 € ha⁻¹ in costs at a Spanish and two German sites, respectively, but no such savings potential was estimated for four other sites. Investment costs reduce in the long term when the machinery endowment can be gradually adjusted to reduced machinery requirements (see Section 4.4).

In Mediterranean, water-limited sites of Spain, cereals following grain legumes reacted with slightly increased or maintained yields to reduced or zero tillage, which resulted in increased GMs (Sánchez-Girón et al., 2004; López-Bellido et al., 2012). Also reduced yields of a vetch-barley rotation have been reported with reduced tillage in central Spain (Soldovilla-Martinez et al., 2013), but this may not negatively affect GM considering potential cost reductions. Applying reduced tillage to all crops in the rotation is also feasible, as the grain legume crops themselves were found to react with maintained or even increased yields to reduced or zero tillage (López-Bellido et al., 2003, 2004; Ozpinar and Ozpinar, 2011; Giambalvo et al., 2012), and their GM increased relative to other crops (Ozpinar and Ozpinar, 2011). Positive effects of combined reduced tillage and legume rotations have also been shown in Germany, and lead to cost savings of 21% compared to a ploughed cereal-dominated rotation, whereas savings with reduced tillage and cereal dominated rotations were lower (Luette-Entrup et al., 2006). For comparison, in Australia a shift to no-till farming around the year 1990 doubled the yield benefit of wheat following lupins due to high weed pressure and few control options in pure cereal sequences under no-till farming (Seymour et al., 2012).

4. Farm-economic competitiveness of grain legumes and consideration of their pre-crop benefits

4.1. Competitiveness at crop level

When considering grain legumes in crop choice, farmers are often faced with their low farm-economic value according to standard assessments conducted at crop level, i.e. low GM and high production risks compared to competing crops. Only in five out of twelve case studies, grain legumes had higher GMs than an alternative crop (Table 2, highlighted in bold). They were more likely to be competitive with less profitable cereals such as barley, rye, or maize (4 out of 5 cases, Table 2), than with wheat (2 out of 10 cases), or alternative broad-leaved crops such as rapeseed or sunflower (1 out of 8 cases). This implies that the typical comparison to wheat underestimates grain legume competitiveness for diversifying cereal-dominated rotations (Bues et al., 2013). Conversely, the rarely compared alternative break crops (i.e. broad-leaved crops or oats that ‘break’ continuous cereal sequences) are the main competitors of grain legumes both economically and due to their similar role in crop rotations. Also Brsson et al. (2010) show that rape is a major competitor of grain legumes in France: from 1999 to 2006, the share of wheat area preceded by grain legumes reduced from 25 to 15%, while that preceded by rapeseed increased from 20 to 30% in the same period. A parallel increase of rapeseed production while decreasing soya production has also been reported from Romania (Popescu, 2012).

In addition to their often comparatively low GM, fluctuations in income from grain legume production reduce their subjective value to a risk averse producer, i.e. their certainty equivalent (Schilizzi and Kingwell, 1999; Lehmann et al., 2013). Farmers avoid growing legumes as a risk aversion strategy, as shown by a survey in four European countries (von Richthofen et al., 2006a). Grain legume yields are considered to be very variable due to crop physiology and technical difficulties e.g. in harvesting (Ayaz et al., 2004; Corre-Hellou and Crozet, 2005; von Richthofen et al., 2006a; Hauggaard-Nielsen et al., 2008; Wright, 2008; Sass, 2009; Jensen et al., 2010; Flores et al., 2012). However, variation of yield and GM are seldom substantially higher than of other crops (Table 3). Instead, variation may be more significant in relation to low overall yield and GM. Growing grain legumes in less favourable sites may negatively influence yield variation statistics.

Where farmers still grow legumes in spite of the mostly low GM and high production risk, they are often motivated by agronomic considerations rather than economic performance (see producer and non-producer surveys by von Richthofen et al., 2006a; Alpmann et al., 2013a). Furthermore, grain legumes can act as a component of within-farm risk diversification strategies (Mishra and Lence, 2005), as they may be differently affected by specific weather conditions than many other crops (see Peltonen-Sainio and Niemi, 2012; Adam et al., 2013; Schäfer, 2013). As cropping decisions are motivated by a broad context of multiple objectives (Janssen and van Ittersum, 2007; Dury et al., 2013), farmers may choose grain legumes because they fit a particular farming strategy such as on-farm feed production (Alpmann et al., 2013b), organic farming (Robson et al., 2002), and reduced tillage systems (Luette-Entrup et al., 2006). Or they may not choose them because particular preconditions are lacking, such as availability of inputs and marketing possibilities, or the capacity to utilise additional organic N in regions with high stockings densities (Weitbrecht, unpublished; von Richthofen et al., 2006a; LMC International, 2009b). The described benefits of grain legumes to cropping systems call for expanding grain legume GMs beyond the crop level.

4.2. Expanded gross margins - estimation of pre-crop value

Several authors, e.g. Beattie et al. (1974), Weitbrecht and Pahl (2000) and Schäfer (2013), have argued for crediting the economic benefits of grain legumes on subsequent crops, i.e. their ‘pre-crop value’, to the grain legume GM itself and for deducting this value from the GM of the subsequent crop. Thereby, the GMexp of grain legumes and their subsequent crops converge partially and the grain legume may become competitive with a less profitable cereal. Several estimations of this pre-crop value relative to pure cereal sequences in Germany, vary greatly from 78 € ha⁻¹ to more than 500 € ha⁻¹ (Table 4), due to a wide range of estimated yield benefits (0–2.5 Mg ha⁻¹) and to differences in cost reductions assumed; the largest figures may be less realistic because highest yield benefits and highest cost reduction are unlikely to be realised simultaneously.
Table 2
Crop gross margins (GM) without subsidies of grain legumes compared to alternative crops in Europe.

<table>
<thead>
<tr>
<th>Case study, year (source)</th>
<th>Grain legume</th>
<th>Gross margin advantage of grain legume compared to...</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wheat</td>
</tr>
<tr>
<td></td>
<td>Crop</td>
<td>Yield (Mg ha(^{-1}))</td>
</tr>
<tr>
<td>Netherlands, 2008 Kamp et al. (2010)</td>
<td>Faba bean</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Pea</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>Lupin</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Pea</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Faba bean</td>
<td>3.6</td>
</tr>
<tr>
<td>France, Eure et Loir, 2001–2007 LMC International (2009a)</td>
<td>Pea</td>
<td>4.5</td>
</tr>
<tr>
<td>France, Seine Maritime, 2001–2007 LMC International (2009a)</td>
<td>Pea</td>
<td>5.0</td>
</tr>
<tr>
<td>France, Midi Pyrénées rainfed, 1999–2003 (Mahmood, 2011)</td>
<td>Soya bean</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Pea</td>
<td>2.4</td>
</tr>
<tr>
<td>Germany, Niedersachsen, 2001–2007 LMC International (2009a)</td>
<td>Faba bean</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Pea</td>
<td>3.6</td>
</tr>
<tr>
<td>Poland, 2005 LMC International (2009a)</td>
<td>Faba bean</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Pea</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Soya bean</td>
<td>3.0</td>
</tr>
<tr>
<td>Germany, Rhineland-Pfalz, 2009 Zilles (2010)</td>
<td>Faba bean</td>
<td>3.9</td>
</tr>
<tr>
<td>Finlan, Southern, 2011 Peltonen-Sainio and Niemi (2012)</td>
<td>Pea</td>
<td>2.4</td>
</tr>
<tr>
<td>Spain, Castilla-La Mancha, 2001–2007 LMC International (2009a)</td>
<td>Faba bean</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Positive GM advantages highlighted in bold. Production subsidies were subtracted from original data. Note that data from different sources cannot be compared as they relate to different time-spans and a different range of costs was taken into account. E.g. Kamp et al. (2010) included machinery fuel, Mahmood (2011) included labour costs, Zilles (2010) assumed high costs for contractor tillage and harvesting and LMC International (2009a) assumed high grain drying costs in the site Seine Maritime.

Data of: a Cambridge University.
b UNIP.
c ZMP.
### Table 3
Variation in yields and returns of grain legumes compared to other crops.

<table>
<thead>
<tr>
<th>Source and details</th>
<th>Site</th>
<th>Pea</th>
<th>Faba bean</th>
<th>Rapeseed</th>
<th>Wheat</th>
<th>Barley</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Yield variation</td>
<td>Schäfer (2013)</td>
<td>Germany</td>
<td>9.4</td>
<td>10.0</td>
<td>13.8</td>
<td>6.9</td>
<td>8.5</td>
</tr>
<tr>
<td>National yield, 20 yrs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelkonen-Sainio and Niemi (2012)</td>
<td></td>
<td>Finland</td>
<td>9.0</td>
<td>11.6</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>National yield [5-yr moving average], 1997–2007</td>
<td></td>
<td>France</td>
<td>17.4</td>
<td>12.5</td>
<td>13.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Germany</td>
<td>10.3</td>
<td>10.2</td>
<td>6.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spain</td>
<td>11.5</td>
<td>12.7</td>
<td>6.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sweden</td>
<td>10.2</td>
<td>8.4</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regional yield, 2000–2011</td>
<td>Southern Finland</td>
<td>7</td>
<td>7</td>
<td>13</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>(B) Gross margin variation</td>
<td>LMC International (2009a)</td>
<td>Seine Maritime, France</td>
<td>25</td>
<td>33</td>
<td>16</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Regional gross margin, 2001–2007</td>
<td>East Anglia, UK</td>
<td>31</td>
<td>36</td>
<td>49</td>
<td>23</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Castilla La Mancha, Spain</td>
<td>78</td>
<td>42</td>
<td>48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eure et Loir, France</td>
<td>31</td>
<td>22</td>
<td>29</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower Saxony, Germany</td>
<td>51</td>
<td>46</td>
<td>35</td>
<td>34</td>
<td>21</td>
<td></td>
</tr>
</tbody>
</table>

* Coefficient of variation equals variance divided by arithmetic mean.

### Table 4
Gross margin benefits or pre-crop value of grain legumes to subsequent cereals compared to pure cereal sequences in Germany.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased revenues</td>
<td>1st subsequent crop</td>
<td>158&lt;sup&gt;a&lt;/sup&gt;</td>
<td>35-105&lt;sup&gt;b&lt;/sup&gt;</td>
<td>125-250&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0-251&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>2nd subsequent crop</td>
<td>25&lt;sup&gt;f&lt;/sup&gt;</td>
<td>35-105&lt;sup&gt;b&lt;/sup&gt;</td>
<td>25-27&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduced costs</td>
<td>N fertiliser</td>
<td>27&lt;sup&gt;f&lt;/sup&gt;</td>
<td>10-50&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5-30&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0-16</td>
</tr>
<tr>
<td></td>
<td>Tillage</td>
<td>34</td>
<td>20-60</td>
<td>20-60</td>
<td>70-125&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Herbicides</td>
<td>0-50</td>
<td>0-45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fungicides</td>
<td>20-50</td>
<td>0-45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>&gt;244</td>
<td>78-225</td>
<td>175-510</td>
<td>128-347</td>
<td>120-140</td>
</tr>
</tbody>
</table>

Basis for calculation:
- <sup>a</sup> extra yield 0.6 t, price 250 €/t;
- <sup>b</sup> extra yield 0.4-1.2 t, price 108 €/t;
- <sup>c</sup> extra yield 0.5-1.0 t, price 250 €/t;
- <sup>d</sup> extra yield 0-2.5 t, price 100 €/t;
- <sup>e</sup> extra yield 0.1 t, price 107 €/t, harvesting costs 15 €/t;
- <sup>f</sup> extra yield 0.1 t, price 250 €/t;
- <sup>g</sup> extra yield 0.1-0.3 t, price 250 €/t;
- <sup>h</sup> extra yield 0.02 t, price 103 €/t, harvesting costs 15 €/t;
- <sup>i</sup> saved N 27 kg, price 1 €/kg;
- <sup>j</sup> saved N 40-80 kg, price 0.55 €/kg;
- <sup>k</sup> saved N 5-30 kg, price 1 €/kg;
- <sup>l</sup> saved N 5-24 kg, price 0.5 €/kg.

However, pre-crop value is always relative to the production alternative and the measure becomes more complicated to apply when grain legumes are to be compared to alternative break crops, which is required to gain conclusive insights. Other break crops would have to be credited with their pre-crop values as well and even where the pre-crop value of a grain legume seems very high, expanded GMs would hardly converge. The reported fertiliser savings of mostly less than 30 € ha<sup>−1</sup> alone (as estimated in Tables 1B and Table 4), may not suffice to significantly improve the competitiveness of grain legumes over alternative break crops.

#### 4.3. Rotation gross margin

Seven studies have assessed the profitability of grain legumes by comparing the modelled average annual GM of rotations (GM<sub>rot</sub>) with and without grain legumes, with pre-crop-specific yields and production costs (Table 5, details indicated in supplementary data, Table A3). Altogether, the average annual GM<sub>rot</sub> of 27 of the 53 grain legume rotations was advantageous over that of a comparable rotation without grain legumes, and in another eight comparisons minor GM<sub>rot</sub> deficits occurred (less than 10 € ha<sup>−1</sup> difference) that may not be relevant under practical conditions, therefore 35 out of the 53 tested rotations are considered competitive. However, differences between sources and sites, partly caused by differences in production systems and model assumptions, complicate the comparison of results. While all included studies considered the pre-crop benefit of grain legumes on yield of 1st subsequent crop and N fertiliser costs, reduction in tillage costs were included only by von Richthofen et al. (2006b) and Hayer et al. (2012), and pesticide savings only by von Richthofen et al. (2006b). Furthermore, the definition of crop rotations to be compared, usually based on expert knowledge, can greatly influence results.

Competition of grain legume rotations shown in Table 5 differs among countries. The highest advantage of grain legume rotations over non-legume rotations was reported from Romania with 418 € ha<sup>−1</sup>, due to high yield benefits and high value of food legume production. Grain legumes were competitive with or advantageous over non-legume rotations in Spain due to the...
low profitability of alternative crops. In Italy, the performance of grain legume rotations differed strongly between the lowland and hillside sites due to different crops grown. Furthermore, the majority of grain legume rotations in France and half of the rotations in the UK were competitive or advantageous. For Germany and Spain, the compiled studies tested different production systems. Grain legume rotations compared positively against those without legumes in organic production systems with more than 70 € ha\(^{-1}\) higher GM. Part of the advantage of one organic rotation may be due to food soy production with high producer prices. Only one competitive rotation was found by the three references referring to conventional production in Germany (Table 5).

In trials with different tillage systems (Table 5), the benefit of grain legume rotations increased with reduced tillage: at three sites in Germany, five of the eight tested rotations compared positively against non-legume rotations with up to 115 € ha\(^{-1}\) higher GM (Luetke-Entrup et al., 2006), and in Spain, the benefit of the grain legume rotation doubled from 49 to 97 € ha\(^{-1}\) with ploughing and zero tillage, respectively (Sánchez-Girón et al., 2004).

No competitive grain legume rotations were found for Denmark, Sweden, and Switzerland (Table 5), and the rotation reported from Switzerland compared worst against non-legume rotations with 180 € ha\(^{-1}\) deficit, due to overall high revenues of the cropping sequences. These results for specific countries are partly confirmed by national grain legume production trends since 2000 (FAOstat, 2014): Grain legume production areas remained relatively less affected in Romania and Spain (17% reduction in 2000–2012), reduced moderately in the UK, Italy, France, and Germany (20–50% reduction) and more strongly in Sweden and Denmark (50–80% reduction). However, increasing grain legume areas in Switzerland show that the assessed crop rotation result cannot be generalised (40% increase). The mostly eastern European countries where production areas increased since 2000 are not represented in the compiled studies.

The GM\(_{\text{rot}}\) support the observation that grain legumes are more likely to be competitive with cereals than with break crops when their pre-crop value is considered. As Table 5 shows, a rotation where a grain legume displaces a cereal crop or where it was inserted between two consecutive cereals was in most cases competitive with the original rotation, whereas displacement of a broad-leaved crop (rapeseed, sunflower, maize, linseed) was more often not competitive.

### 4.4. Inclusion of fixed labour and machinery costs

As a reduction in peak labour demand and tillage requirements with grain legumes enables reducing machinery endowment (see Section 3.5), Luetke-Entrup et al. (2006) found that whole-farm conservation tillage with grain legumes saves 36% of fixed machinery costs and 26% of labour time requirements compared to yearly ploughing with cereal-dominated rotations. They argue that such labour and fixed machinery costs should be included in measures of competitiveness of grain legume farming systems by calculating a rotation GM less any labour and machinery costs (GM\(_{\text{dal}}\), see Section 2.3).

The GM\(_{\text{dal}}\) for experimental rotations with different tillage systems is shown in Table 6. Under reduced tillage, all grain legume rotations compared positively to non-legume rotations using this measure, with an average annual benefit of 36–158 € ha\(^{-1}\) for 150 ha model farms and 39–189 € ha\(^{-1}\) for 300 ha model farms.
Reduced tillage with legume rotations compared even more favourably against conventional tillage without legumes, with an average annual benefit of 47–162 and 60–165 € ha\(^{-1}\) for the two modelled farm types, respectively. The competitiveness of grain legumes under reduced tillage is higher on larger farms and differs greatly between sites. It is also far higher than when the same grain legume rotations were assessed by GM\(_{\text{DAL}}\) (Table 5).

Since no studies were found that applied other measures sensitive to machinery requirements, i.e. net margin, semi-net margin, or whole-farm cost and performance (see Section 2.3) to a comparison of cropping with and without grain legumes, these measures and GM\(_{\text{DAL}}\) cannot be compared with respect to their suitability. The GM\(_{\text{DAL}}\) appears to be simpler to calculate while encompassing all relevant cost positions. On the other hand, it is not internationally applied and therefore more complicated to communicate or compare with other studies.

### 5. Discussion

#### 5.1. Results discussion

The competitiveness of sole cropped grain legume production in Europe depends to a large degree on the magnitude and value of their pre-crop benefits. Crops following grain legumes achieve large absolute yield benefits even at high fertilisation, both in temperate and Mediterranean sites, when compared to cereal or oats pre-crops. Expanded forms of GM confirm the high pre-crop value of grain legume pre-crops compared to cereal sequences, increasing the number of situations where they are competitive. In contrast, the additional pre-crop benefit of grain legumes compared to other break crops has not been studied as much and its magnitude and value is estimated to be positive but minimal, and it can only in some cases influence grain legume competitiveness.

In spite of significant progress in understanding the processes of rotation effects of grain legumes, their magnitude remains difficult to grasp because they are very variable and specific to agro-economic situations, specifically N level and compared crop, and possible cost savings have only been estimated. Only small amounts of N fertiliser savings are economically feasible without inadequate management effort or risking a trade-off with yield potential (Table 1), explaining typical farmer practice of minimal fertiliser reduction following grain legumes.

Few studies have included the substantial magnitude and value of pre-crop effects in assessments of cropping systems with grain legumes, such as bio-economic modelling and sustainability assessments like LCAs, to enable their consideration in policy and economic decisions relating to grain legume production; examples are assessments in the EU-funded research project Legume Futures. Rotation GM appears to be the most simple and transparent indicator to reflect grain legume profitability with their effects beyond crop level, and has been applied in some international studies. However, calculations of rotation GM are sensitive to the model’s assumptions about the size and value of pre-crop benefits and often rely on expert knowledge or individual experimental results.

Empirical rather than modelled research could increase certainty, but only one such study was identified for Europe (Luetke-Enrup et al., 2006). This review helps to base model assumptions on a broader range of empirical findings, such as the inner quartile range of pre-crop benefits found in European experiments (Fig. 2), and details in the appendix can help to identify experimental results for specific regions or farming systems. However, eastern, south-eastern and northern European countries, as well as France, are insufficiently covered by the data. Due to large variation and limited geographical range, experiments on pre-crop effects covering different regions and crops systematically, and including novel grain legume crops for respective regions such as lupins and soya bean, would be required.

#### 5.2. Grain legumes in Europe compared to other regions

The competitiveness of grain legume production in Canada and Australia greatly contrasts that in Europe (in Canada especially chickpea, lentil and some types of pea, in Australia mainly chickpea and lupins). Since the 1980s, production increased greatly in both countries (Schilizzi and Kingwell, 1999), in the case of Canada making it the world’s leading producer and exporter of pea (Zentner et al., 2002; LMC International, 2009a). Due to the stronger cereal dominance and lower production intensity, grain legume pre-crop benefits are higher and more valuable relative to the overall moderate yield level (Seymour et al., 2012; Zentner et al., 2002), compared to Europe. Grain legumes then displaced summer fallow, cereals, and pasture sequences, increasing the value and diversity of production, but rapeseed has also gained in production areas and has become the most widely grown non-cereal crop and a major competitor of grain legumes since the 1990s (LMC International, 2009a; Seymour et al., 2012). Furthermore, most grain legumes grown in both countries target, at least partly, food markets; therefore they receive higher and more stable prices than feed-targeted grain legumes mostly grown in Europe (LMC International, 2009a).

Accordingly, grain legume production was found highly profitable in all major climatic zones of Canada (Zentner et al., 2002), and chickpea–cereal rotations were found to provide increased revenues in Australia, even when income uncertainty was taken into account (Schilizzi and Kingwell, 1999).

Hence, grain legumes are less attractive crops in Europe than in Australia and Canada, because high production intensity leads to high yield advantages of cereals that can often not be outbalanced by the price differences of legumes and cereals, especially when legume production is targeted at feed markets. Furthermore, the pre-crop benefit of grain legumes is lower in relative terms (percent yield increase) than in Australia and Canada, and comparable to that of competing alternative break crops.

#### 5.3. Outlook

Future competitiveness of grain legumes in European farming systems will depend on policy, market, as well as agronomic and scientific developments. With respect to policy, grain legumes may
find a new production niche as the new EU common agricultural policy recently accepted legume production as one of few harvestable uses of ecological focus areas (currently required on 5% of farmland) and member states are given some limited options to reward environmental benefits of or directly support legume production. A reduction in European policy support for bioenergy crops can be anticipated following debates on their CO₂-efficiency and effect on food production; this would decrease competition of rapeseed and energy maize with grain legumes for land as well as on feed markets.

With respect to markets, increases in the prices for fertiliser N, pesticides or legume grain relative to the prices of alternative crops could improve legume competitiveness (Schilizzi and Pannell, 2001), but over the past decade, no significant relative changes occurred in spite of a rising energy and overall price level, possibly due to accelerating demand for bioswet (Westhoff, 2009). Legume grain prices could relatively increase with a stronger targeting of food markets and novel processing (e.g. Papendiek et al., 2012). Grain legume prices or at least their on-farm feed value (Sauermann, 2009; UFOP, 2014) could also rise with price increases of other protein foods, i.e. higher soy import prices or lower rapeseed meal production (Zander et al., unpublished).

On-going agronomic developments that may positively influence grain legume production are expansion of reduced tillage (López-Bellido and López-Bellido, 2001; Sánchez-Girón et al., 2007; Siddique et al., 2012), expansion of organic farming (Robson et al., 2002), or negative developments in non-legume cropping systems (Schäfer, 2013). Research progress could improve legume agronomy and breeding (e.g. Gillor and Cadiš, 1995; Jensen et al., 2011), efficient utilisation of legume N provision, e.g. through intercropping (e.g. Caviglia et al., 2011; Hauggaard-Nielsen et al., 2008; Lithourgidis et al., 2011; Pappa et al., 2012; Pelzer et al., 2012; Podgorska-Lesiak and Sobkowicz, 2013), or facilitate complex management decisions associated with diversified cropping systems (e.g. Bachinger and Zander, 2007; Reckling et al., 2012).

6. Conclusion

Grain legume pre-crop value is a crucial component of their farm-economic profitability in European cropping systems that needs to be taken into account for policies and research on agricultural landscape management. Yield benefits to subsequent crops are the major component of pre-crop value but experimental results on their magnitude vary widely and require distinction between climatic regions. N fertiliser intensity, and compared crop. Under typically higher yield levels in Europe, the yield benefit and possible cost savings for fertilisers and biocides are substantial, but their relative contribution is lower than has been reported from other regions of the world, explaining the small production areas farmers dedicate to grain legumes.

The pre-crop value has been considered in economic assessments of grain legumes using different forms of expanded gross margins, primarily rotation gross margins. Considering the pre-crop value increases the number of situations where grain legumes are competitive with cereals, and, to a lower extent, with alternative break crops. Besides a better consideration of their pre-crop value, further political support, supportive market development and genetic and agronomic improvement are needed to enable Europe to grow more legumes, utilise their environmental benefits, and increase the sustainability of its farming.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2015.01.012.

References


