Finding the value of novel feedstuffs in imperfect markets, taking *Lupinus albus* as an example

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Abbreviations:

AES = agri-environmental schemes; DM = dry matter; DSS = decision support system; LP = linear programming; ME = metabolizable energy; ML = maximum likelihood; NEL = Net-energy lactation; nXP = usable crude protein

Abstract

Feed production and utilization are significant contributors to agricultural economic performance. Upon the market entry of new feedstuffs, livestock farmers are challenged to determine their price worthiness. In addition, transparent price formation is also hampered under the conditions of new and often imperfect markets, thereby negatively impacting trade and impeding the development of sustainable markets. Therefore, this study proposes a decision support system that enables the effective valuation of novel feeds, such as white lupin (*Lupinus albus L.*). The proposed system was based on a linear optimization model that, by parameterizing the pricing assumption of novel feeds, determined their substitution value relative to conventional feeds. Notably, the substitution value of white lupin as a feed was found to vary significantly by animal species, production process, performance level, and cultivation year. However, with substitution values up to €557 t^{-1}, the value of white lupin was frequently far higher than the rarely available market prices (€270 t^{-1}, as of 12/2021), suggesting that white lupin is a novel feed that is grossly undervalued due to imperfect market conditions. Overall, the proposed system can be used for objective pricing in these cases.

Keywords

Substitution value; Lupin; Feed; Optimization; Linear Programming; Imperfect Market

1 Introduction

Feed is essential in the agricultural sector as it is typically the most important production input in livestock production: its quantity, quality, and price determine the performance, health, welfare, and economics of livestock production. In crop production, feed is often grown to generate income through sale or for use as animal feed. In addition, significant amounts of feeds are obtained as byproducts in the industrial and food sectors, where they generate additional income.

In transparent market systems with numerous suppliers and consumers, pricing of relevant feedstuffs such as various types of grain, soybean meal, and rapeseed meal is based on quantity and nutritional value. Pricing in these markets is therefore valid. For newly introduced feeds, the nutritional value often undergoes an initial assessment. (Meng *et al.*, 2021; Robinson *et al.*, 2008; Wang *et al.*, 2005). If the outcome is favorable, the next step is to establish the new feed in practical use (Lau Heckman *et al.*, 2020), with pricing playing a key role. However, due to conditions in new, imperfect markets characterized by a lack of transparency, few suppliers and buyers, and no clear quality criteria, price determination is severely hampered. For this reason, the price worthiness of rapeseed cake and rapeseed meal was discussed years ago (Schöne, 1998). Several studies have revealed methods for determining the price worthiness of feeds. For instance, Sepngang *et al.* (2018) and Roth-Maier *et al.* (2004) used Löhr's exchange method to determine the price worthiness of different grain legumes based on the substitutes of winter wheat and soybean meal. The system of equations used was based on balancing the supply of energy (MJ ME) and lysine or praecaecal digestible lysine in pig feeding. Similarly, balancing energy (MJ ME; MJ NEL) and crude protein or usable crude protein was used in ruminant feeding. Sepngang *et al.* (2018) concluded that this method tended to overestimate the feed value because only a few value-determining parameters were included in the calculation.

St-Pierre and Glamocic (2000) also critically assessed this method under the term "Petersen method" (Petersen, 1932) and developed the maximum likelihood (ML) method. This method is primarily based on the principle of utilizing all relevant marketable feeds to determine the value of a nonmarketable feed, as opposed to relying solely on selected substitutes. Similar to the Löhr or Peterson method, the feed's value-determining nutrients are then priced. Because the ML method can use any number of nutrients and feedstuffs, an econometric model approach with an error term is chosen. For more detailed information, readers should refer to the original publication (St-Pierre and Glamocic, 2000). Although the ML method incorporates all relevant nutrients and feeds to determine feed value, pre-selection is required, which may influence the outcomes.

Both studies (Sepngang *et al.*, 2018; St-Pierre and Glamocic, 2000) also referred to the linear programming (LP) method as an alternative way of determining feed value. LP has been widely used for minimizing ration costs for many years (Tozer, 2000; O'Connor *et al.*, 1989; Waugh, 1951). Overall, the goal is to minimize an economic objective function while adhering to restrictions specific to the feed and the farm. In addition to optimal ration composition, LP applications also provide shadow prices for feed or nutrients, but these shadow prices are valid only for specific situations.

Sepngang *et al.* (2018) considered the LP approach to be of little practical use due to its complexity, whereas St-Pierre and Glamocic (2000) stated that the greatest challenge is that feed valuation cannot be generalized using LP. However, this is also true for their ML method, as pre-selection of the value-giving nutrients ultimately depends on the type of animal being fed, production process, and intended performance level.

Finally, the non-generalizability of feed valuation based on the LP method could be overcome by providing a user-friendly LP-based decision support system (DSS) to determine the price worthiness of novel feedstuffs on an individual and situational basis. Numerous applications exist for such DSSs. For instance, some studies are currently exploring the potential of using insects as feed (Toral *et al.*, 2022; Abd El-Hack *et al.*, 2020; Gasco *et al.*, 2018). The European Union has already begun using the first products as feed. Products classified as feed additives under Regulation (EC) No 999/2001 are not subject to specific approval requirements. Although the widespread use of these products cannot yet be established, the evaluation of their price worthiness is a relevant task.

White lupin (*Lupinus albus*) has gained increased acceptance as an animal feed, and its popularity is increasing globally due to recent price development, especially in the markets for GMO-free soybean meal. Despite the regional support of grain legume production in German agricultural policy, white lupins are almost exclusively grown on farms with an on-farm feed use rather than for commercialization (Sepngang *et al.*, 2018). Compared to alternative crop options, the potential gross output of lupins is low. This deficiency is primarily attributed to the market prices for lupins driven by low, retailer-placed bids. For example, in December 2021, a price of €270 per ton of white lupin was offered at the Triesdorf site (southern Germany), whereas the potential selling price of soybeans was €650 per ton. This discrepancy, with similar cultivation costs, prevents arable farmers from growing lupins. Notably, despite the promising nutritional properties of lupin, the (substitution) value of this protein-rich legume is currently grossly undervalued, considering its market prices. Sepngang *et al.* (2018, p. 10) also concluded as follows:

"Observed market prices and thus market price reports systematically and persistently underestimate the value of legumes." (Translation by author)

This study investigates the value of novel feedstuffs using white lupin as an example. The aim is to develop a DSS to determine the price worthiness of novel feedstuffs under imperfect market conditions. A realistic evaluation of the price worthiness of feed is crucial for potential users, retailers, and producers. Here, we hypothesize that the realistic price worthiness of white lupin significantly surpasses its existing market price. Addressing this issue is expected to help strengthen white lupin cultivation in Europe, resulting in increased self-sufficiency in protein-rich feed, greater biodiversity in the agricultural landscape, and partial substitution of soybeans imported under at times harmful climate effects (Escobar *et al.*, 2020; Castanheira and Freire, 2013). The proposed DSS has direct relevance not only to agriculture and the agricultural sector but also, in this particular application, to important political and societal goals within Europe.

2 Materials and methods

Two values are particularly relevant when establishing fair market prices for non-market feeds. The first is the achievable substitution value of a feed when used in animal feeding. Here, an LP model is used to determine the substitution value and input level of a novel feed relative to established feeds by parameterizing price assumptions (in constant scale rates). The second entails assessing the production and processing costs of novel feeds. Notably, the long term establishment of novel feeds is guaranteed only when the former value surpasses the latter value. In Section 2.2, the production costs are calculated as the total cost.

2.1 Determining substitution values of novel feedstuffs using LP

To determine the substitution values of the novel feedstuffs using LP, a comparison with alternative and market feedstuffs is necessary, with the nutritional content and prices of these feeds playing relevant roles. The price data considered in this study refer to August 2022 (Börlein, 2022). In addition, considering individual feed analyses is crucial in the feed valuation of grain legumes because the nutritional content, in particular the protein content, can vary substantially (Losand *et al.*, 2020). Therefore, for white lupin, own samples from 2019, 2021, and 2022 were analyzed. Table A1 in the Appendix presents an overview of the studied feeds with their prices and content details. Another important component is feeding restrictions imposed on animal type and production process (Table 1). In this respect, the study is limited to the feeding of dairy cows, fattening pigs, and lactating sows.

Table 1: Feeding restrictions

a) Dairy cow feed ration		
- **Farm-specific information and restrictions [a]**		
Live weight dairy cow	=	750 kg
roughage content in the total ration	=	66% of total DM [b]
maize silage	=	50% of roughage DM
grass silage	=	50% of roughage DM
Milk production (4% fat, 3.6% protein)	=	30 kg per day
White lupins	≤	3,5 kg DM per cow and day; max. 45% in concentrate feed [h]
- **General restrictions [b]**		
Daily DM intake per cow	≤	3% of live weight
Daily energy requirement (NEL)	≥	As per calculation
Daily nXP requirement	≥	As per calculation
Crude fiber	≥	16% of total DM
aNDF [c]	≥	28% of roughage DM
Crude fat	≤	4,5% of total DM
Rumen nitrogen balance (RNB)	:	−10 to 10 g per day ration
b) Fattening pig feed ration (early stage; daily gains of 850 g) [d]		
Daily energy requirement (ME)	≥	30 MJ
Energy density	:	13,0 to 13,4 MJ ME per kg dry-feed [e]
Lysine content in relation to energy	:	0,8 to 0,9 g per MJ ME
pcv-lysine [f]	:	80% to 90%
Crude protein	:	170 to 180 g per kg dry-feed [e]
Calcium content in relation to energy	=	0,55 g per MJ ME
Digestible phosphorus (dP) to energy	=	0,25 g dP per MJ ME
White lupins	≤	15%–20% of dry-feed [e,g]
Crude fiber	≥	4% of dry-feed [e]
c) Lactating sows feed ration [d]		
Daily energy requirement (ME)	≥	95 MJ with litter mass gain of 3 kg per day
Energy density	:	13,0 to 13,4 MJ ME per kg dry-feed [e]
Lysine content in relation to energy	:	0,70 to 0,75 g per MJ ME
pcv-lysine [f]	:	82% to 90%
Crude protein	:	165 to 175 g per kg dry-feed [e]
Calcium content in relation to energy	=	0,55 g per MJ ME
Digestible phosphorus (dP) to energy	=	0,25 g per MJ ME
White lupins	≤	15% of dry-feed [e,h]
Crude fiber	≥	4% of dry-feed [e]

Remarks: [a] The given values are exemplary and have to be adapted to the farm; [b] According to Federal Advisory Data (Bayrische Landesanstalt für Landwirtschaft, 2021a, pp. 28–31); [c] Neutral detergent fiber after amylase treatment; [d] If not stated otherwise, then based on data from the Federal Advisory Service (Bayrische Landesanstalt für Landwirtschaft, 2021b); [e] Dry-feed at standardized dry matter content of 88%; [f] pcv = Praecaecal digestible; [g] (van Barneveld, 1999; Donovan *et al.*, 1993); [h] (Durst *et al.*, 2021).

By synergizing the feed (Table A1) and feeding requirements (Table 1), animal- and production-specific LP models can be established. These models are based on the following structure (modified after Andrei, 2013, p. 119):

$$\textit{minimize} \qquad f(x) \tag{1}$$

$$\textit{subject to:} \qquad g(x) \leq 0 \tag{2}$$

$$h(x, y) = 0 \tag{3}$$

$$x \in \left[x^L, x^U\right]. \tag{4}$$

Here, the monetary objective function *f* as well as the sample constraint functions *g* and *h* represent linear functions. The variables *x* correspond to different feeds, which may be restricted in quantity by a permitted solution space between the lower bound *L* and upper bound *U*. The feeding requirements play the role of restrictions, which are represented in the constraint functions *g* and *h* in the form of inequalities or equations. To determine the value of novel feeds, the linear objective function must be minimized. Novel feeds are used only if their prices are competitive. The maximum price at which a novel feed can still be used is identified as its maximum substitution value. To identify the substitution value, the LP model is solved several times, iteratively increasing the price of the relevant feed until its level of use is zero. Through this procedure, known as LP model parameterization in constant scale rates, the price at which a novel feed becomes a viable substitute can be determined.

2.2 Production costs of white lupin

The pricing of feedstuffs is significantly impacted by production costs. Because their cultivation methods and products are similar, the cultivation of white lupins is often compared to that of soybeans. However, many farms are not looking to replace soybean cultivation with lupin. Therefore, comparing white lupin with an established crop rotation would be more relevant. To assess the production costs of white lupin from the perspective of a cash crop farm, a quadruple crop rotation of winter wheat (B-quality), winter oilseed rape, corn, and summer barley was chosen and combined into a multi-crop gross margin. Table 2 lists the gross margins, including the calculation method and detailed information on the data used. To eliminate possible cost effects due to different machine utilization at the farm level, all production processes were assumed to be conducted entirely by contractors. Therefore, the gross margins already include both the factor costs for productive labor and machine costs.

Table 2: Comparison of selected gross margins

			White lupine	Soybean	CR[a] (WW, WR, GM, SB)
	Yield	t ha^{-1}	3.26 [b]	3.14	6.72 [c]
	Price	€ ha^{-1}	345.9	610.0	388.5 [c]
	Gross output	€ ha^{-1}	1127.63	1915.40	2321.47
-	Seeds (100% purchased)	€ ha^{-1}	290.00 [d]	392.19	123.21
-	Nitrogen (removal)	€ ha^{-1}	−83.13 [e]	−72.06 [e]	317.24
-	Phosphorus (removal)	€ ha^{-1}	33.90	48.98	65.19
-	Potassium (removal)	€ ha^{-1}	39.77	65.12	49.16
-	Chemicals (medium intensity)	€ ha^{-1}	90.30	117.90	146.43
-	Services (complete)	€ ha^{-1}	461.11	467.35	541.88
-	Cleaning, drying	€ ha^{-1}	130.60	164.10	198.33
-	Hail insurance	€ ha^{-1}	41.90	53.60	66.65
-	Capital costs for current assets [f]	€ ha^{-1}	15.07	18.56	24.85
=	**Gross margin**	€ ha^{-1}	**108.11**	**659.66**	**788.54**

Remarks: Unless otherwise indicated, data are from the online application "LFL-Deckungsbeitragsrechner" (Reisenweber *et al.*, 2022), for all of Bavaria. Price data are without VAT. According to the above-mentioned online application, producer prices and costs refer to the planning year 2022, while yield data refer to average yields from 2017 to 2021. To exclude individual farm mechanization effects, it was assumed that all operations were performed by contractors; a CR = Crop rotation of winter wheat (WW), winter oilseed rapeseed (WR), corn (GM) and spring barley (SG); b Average yield of white lupin (varieties: Frieda, Selina) measured on 68 farms in Germany in 2021 (Deutsche Saatveredelung AG); c Mean values over the entire crop rotation of winter wheat, rapeseed, grain maize, and spring barley (25% each); d Own data for seed costs incl. inoculation; e Value from nitrogen accumulation of legumes; f Interest rate of 3% p.a. for current assets (approximate current assets correspond to: 50% of variable costs for summer crops and 60% for winter crops).

Based on the gross margin calculation in Table 2, threshold prices can be derived. From a long term perspective, a total cost-covering price is required to ensure economically viable cultivation. This price is called the profitability threshold. In addition to variable production costs (Table 2), opportunity costs for own factors (in this case, land), as well as fixed and overhead costs, are relevant for the profitability threshold calculation. In the calculation example, the fixed costs refer only to buildings, as complete external mechanization was assumed. Opportunity costs vary depending on the situation. Notably, conventional crop rotation is likely to be displaced, in which case the average gross margin will represent the opportunity cost. If only one crop is replaced (e.g., soybean), the gross margin of this crop is decisive. Like the profitability threshold, the production threshold is also important. It indicates the minimum price at which a producer can economically produce a particular product, at least in the short term. Here use-independent costs, such as fixed and overhead costs, are not considered. Table 3 lists the calculation of the relevant thresholds, including detailed notes.

Table 3: Threshold prices for white lupin production

	(1) Variable production cost [a]	(2) Opportunity cost land [b]	(3) Fixed and overhead costs [c]	(4) Threshold prices [d]
Profitability threshold (Compared to crop rotation)	1020 € ha^{-1}	789 € ha^{-1}	350 € ha^{-1}	662 € t^{-1}
Production threshold (Compared to crop rotation)	1020 € ha^{-1}	789 € ha^{-1}	0 € ha^{-1}	555 € t^{-1}
Production threshold (Compared to Soybeans)	1020 € ha^{-1}	660 € ha^{-1}	0 € ha^{-1}	515 € t^{-1}

Remarks: [a] Variable production costs according to Table 2 (with complete third-party mechanization); [b] Opportunity costs depend on the situation: Substitution of one hectare of crop rotation or direct comparison with soybean (see gross margins Table 2); [c] Use-independent and therefore only relevant in the long term. Consists of: general labor, overheads, fixed costs for buildings; [d] Price from which the production of white lupine becomes viable in the short or long term.

The production and profitability thresholds shown in Table 3 are relatively close to each other because complete external mechanization was assumed. In practice, therefore, lower production thresholds are often expected, as own mechanization is usually involved. Thus, production thresholds are highly farm-specific and must be interpreted with appropriate caution. This also applies to the production thresholds shown in Table 3. In addition to pure production costs, the cultivation of legumes in particular is also associated with additional benefits in the form of positive crop rotation effects. In the gross margin calculation, only the nitrogen fixation was considered with a value of €2.55 kg^{-1} (Table 2) for the following crop. In Germany, legume cultivation is partly subsidized. The Bavarian “cultural landscape program” (KULAP, as of 2022), for example, includes a subsidy of €120 per hectare. This is contingent upon a crop rotation with at least five crops, of which at least 10% are grain legumes, and a limit of 30% per crop. For the exemplary farm with its already four-crop rotation, this means that 10 hectares of lupine cultivation on the total farm area of 100 hectares will generate a subsidy of €12,000 per year. When applied to the yield (3.26 t ha^{-1}; Table 2) of 10 hectares of lupins, this yields a subsidy of €368 per ton of lupins. Such subsidies indeed have a direct influence on the threshold prices mentioned in Table 3.

3 Results

The developed DSS is a key output of this study. This section first explores the structure and handling of this tool. In the second part, the tool is then used as an example of white lupine pricing.

3.1 Notes on DSS structure and operation

The DSS was implemented as an MS Excel application. The containing spreadsheets, “DairyCow,” “FatteningPigs,” “LactatingSows,” and “Feedstuff,” provide all inputs and outputs that are relevant for the user. The tool runs macros and uses the Excel add-in “Solver,” which must be activated first (File/Options/Add-Ins/Solver). The tool is available on request from the authors.

Start with the spreadsheet “Feedstuff” (see Appendix, Table A1), ensuring that all relevant feedstuffs (arranged in columns) are included in it and that current price information and correct information regarding nutrient contents are available. Currently, only the nutrients highlighted in bold are used to calculate the substitution value. In addition, all price data must refer to one and the same point in time; otherwise, the tool will result in meaningless substitution values. Feedstuffs without a known market price should be marked with a question mark in the row “Price.” The right part of the table contains exclusive data for livestock feeding, namely the slack variables “energy deficit” and “nXP deficit,” as well as editable data for selected forages. The slack variables allow temporary energy or nXP deficiency in dairy cow rations, but this leads to penalty costs, which an advanced user can control via the “price setting” of these slack variables. This system of slack variables is necessary because the ration requirements in high-performance dairy cows usually cannot be fully met. Instead, dairy cows respond to temporary nutrient deficiencies using endogenous reserves (Gross *et al.*, 2011; Berglund and Danell, 1987).

Depending on the animal type and production process, one of the spreadsheets “DairyCow,” “FatteningPigs,” or “LactatingSows” must now be selected. The structure of this input and output surfaces are identical in each case:

- Farm-specific information on feeding — Input
- Selection of potentially suitable feed — Input
- Calculate ration and substitution values — Solver
- Ration design and substitution values — Output

The following applies to the user interface (see Appendix A2 for an example): All cells with a green background are input cells that can be adjusted by the user. Labels and notes ensure self-explanatory handling of the user interface. Special consideration should be given to orange-highlighted input cells. Here, the user selects up to two feedstuffs for which a substitution value is to be calculated. If required, the upper limits for their use can be set. With the information on the potential price corridor, the user first defines the lower and upper price limits. The DSS thus tests in several runs whether the use of the respective feed is possible under various price assumptions. The solver is started by clicking on the blue button. This is followed by 11 calculation runs using successively increasing price assumptions for the feeds to be analyzed. The step size used to parameterize the price assumptions results from Equation 5:

$$Step\ size = \frac{(upper\ bound - lower\ bound)}{10} \tag{5}$$

To obtain an initial overview of a feed substitution value, the price corridor should initially be broadly defined. Subsequently, the price corridor can be narrowed down further iteratively by the user to specify the substitution value.

Figure 1 is part of the program output. This shows the maximum substitution value of a feedstuff with the usage level. In this example, the substitution value of lupin (2019) is around €49 per 100 kg. Beyond this threshold, other feeds are preferred.

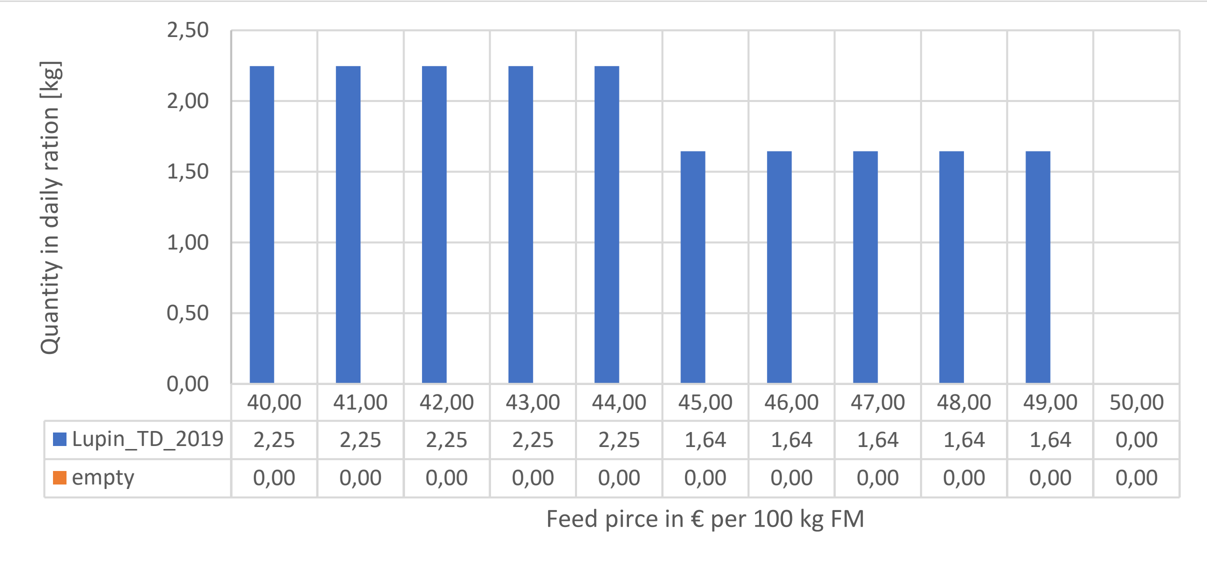

Figure 1: Substitution value and usage level

Additionally, the ration composition and compliance with the ration requirements are tabulated in Appendix Table A3.

3.2 White lupin pricing application

As mentioned earlier, both the production costs from the producers' side and the substitution value from the consumers' perspective are relevant for the pricing of non-marketable feeds. If a price corridor exists for which the substitution value exceeds the production costs, there is a realistic chance of "fair" pricing and sustainable business relationships. To illustrate this using white lupin as an example, its substitution value was compared with the threshold prices on the producer side (Table 4).

Table 4: Comparison of substitution values and producer price expectations

Animal type and performance level		Substitution value **lupin** (Depending on cropping season [a])			Profitability threshold	Production threshold in comparison to:	
		2019	2021	2022		Crop rotation	Soybean
Dairy cow; 25 kg milk day^{-1} [b]	[€ t^{-1}]	557	479	467			
Dairy cow; 30 kg milk day^{-1} [b]	[€ t^{-1}]	492	382	372			
Dairy cow; 35 kg milk day^{-1} [b]	[€ t^{-1}]	0	0	0	**662** (294 [c])	555 (187 [c])	515 (515 [c])
Fattening pig (early state); 850 g daily gain	[€ t^{-1}]	540	474	464			
Lactating sow; litter mass growth 3 kg day^{-1}	[€ t^{-1}]	505	462	452			

Remarks: [a] Varying nutrient contents according to own test results were considered (Table "Feedstuffs" in the appendix); [b] Dairy cow with 750 kg live weight; roughage = 50% grass silage and 50% maize silage; milk contents of 4.0% fat and 3.6% protein; [c] Threshold prices minus subsidy of grained legumes (€368 t^{-1}, compare section 2.2 for further details).

Many findings can be drawn from Table 4:

(i) Due to varying nutrient contents of white lupin, especially for crude protein (compare Annex Table A1), its substitution values differ considerably from year to year. Such annual effects in nutrient content in legumes are well known (Losand *et al.*, 2020). The present results show that individual nutrient analyses of single lots are strongly recommended to determine a substitution value.

(ii) Moreover, animal type, production process, and performance level are relevant for determining a feed substitution value. Table 4 differentiates five exemplary variants, each of which is presented in a separate line of the table. Lupins achieve the highest substitution value in all observed years for dairy cows with a milk production of 25 kg per day. With increasing milk production, the substitution value decreases considerably, attributed to the energy and protein contents per unit of dry matter: since the dry matter intake of the cow is limited, higher concentrated feeds, such as soybean meal, become more important with increasing milk production. Above a milk production of 35–40 kg per day, the ration requirements (Table 1) can no longer be met. The assumed maximum dry matter intake of the cow is reached, which leads to an undersupply of nutrients (energy and protein). This situation is also seen in practice. Because cows use endogenous resources in this phase to compensate for the deficiency situation (Gross *et al.*, 2011; Berglund and Danell, 1987), slack variables were integrated into the DSS to allow temporary energy and protein deficiency ("energy deficit" and "nXP deficit"). The penalty costs for this were purposely set high at €10 per MJ NEL, or per gram of nXP. In this way, there is always an incentive to design a dairy cow ration that meets the needs of dairy cows as much as possible. However, the use of lupin is no longer an option in such a high-performance situation, as this would raise the penalty costs for energy and protein deficiencies. For this reason, the substitution value in this performance level of the dairy cow is €0 t^{-1}. Notably, the assumed level of penalty costs can influence this result. The substitution values achieved in pig feeding (range: €462–€540 t^{-1}) remain unaffected by this penalty cost system.

(iii) The right part of Table 4 shows the threshold prices from the producer's perspective, distinguishing into a situation without and with subsidy.

Situation without subsidy (Table 4, values without brackets): In the long term, it is only profitable for the producer to cultivate lupins at a minimum price of €662 t^{-1}. However, the profitability threshold exceeds the calculated substitution values for lupin in every case (crop year in combination with animal type, and production process). In the short term, the production threshold (compared to the standard crop rotation) of 555 € t^{-1} is relevant for the producer. With a substitution value of €557 t^{-1} in the low production segment, this threshold can only be exceeded in dairy farming. However, this result is insufficient for widespread cultivation and use of white lupin as feed.

Situation with subsidies for the cultivation of grain legumes (Table 4, values in parentheses): Selective subsidization can close the gap between threshold prices and substitution values. For this purpose, EU member states already use funds from the second pillar for agri-environmental schemes (AES). The corresponding Bavarian AES is based on a rotation with at least five corps and a minimum 10% share of grain legumes (Bayrisches Kulturlandschaftsprogramm, as of 2022). This grants a subsidy of €120 ha^{-1} for the entire arable land. The profitability threshold for lupine cultivation is thus already reached at a price of €294 t^{-1}, which closes the gap to the achieved substitution values. However, since the AES in question also applies to soybean cultivation, both crops (lupin and soybean) are subsidized equally. The producer, therefore, has to make the direct economic comparison between lupine and soybean cultivation. In this particular case, lupine cultivation can only prevail over soybean cultivation above a price level of €515 t^{-1}. This result in an absolute price minimum for lupins of €515 t^{-1} for the Bavarian producer under the constellation mentioned. Only a few production processes (dairy cow 25 kg; fattening pig) can meet this price minimum by a higher substitution value.

4 Discussion and conclusion

This study presents a DSS for determining substitution values of non-market feedstuffs. The determined substitution values are only a snapshot because they are highly dependent on the current market prices of the substitutes. Volatile markets therefore require a regular reassessment of substitution values. Furthermore, only the feed consumption of non-market feedstuffs is considered for valuation in the DSS. This technique fails to incorporate the potential alternative uses of these products, such as their utilization for human consumption, which can have a significant impact on their value. This could lead to an underestimation of product value by the DSS.

The DSS was founded on LP, which was then used to parameterize the model. For this purpose, the method of fixed-scale rates was applied, in which the price assumptions of the non-market feeds were increased step by step. However, synergizing both methods resulted in some limitations: (i) Only linear relationships can be represented. This was addressed by providing concrete information on the animal species, production process, and performance level to build static ration requirements. (ii) Due to the chosen parameterization method with fixed scale rates, the substitution value of a feed can only be determined approximately. Precision depends on the selected step size, which can be controlled by the user. This means that several runs may be necessary to determine the substitution value with the required accuracy. Compared to the method of corner point parameterization, where an exact determination of the substitution value is possible, the chosen method has the benefit of allowing the input quantity of the feed in question to be viewed concurrently at various price levels. This information is extremely relevant to the farmer because it clarifies the maximum quantities of feed that can be used at the respective substitution value. Situations in which a particular substitution value results only from marginal input quantities can be identified immediately. (iii) The LP model is based on a pre-selection of restrictions defining ration parameters. The user also pre-selects the model variables or the potential feeds. Both factors affect the substitution value for a non-market feed in the end. Therefore, the results of this study cannot be generalized, as they refer to the individual situation of a farm or a herd. Other methods, such as Löhr or ML, are ultimately subject to the same problems and do not lead to a generalizable valuation. In practice, it may even prove advantageous for the LP-based method to be tailored exactly to the individual farm, as this will expedite decision making. In some cases, LP models are criticized for being too complex for practical use (Sepngang *et al.*, 2018; St-Pierre and Glamocic, 2000). To overcome this, LP model development focused on high user friendliness and low software requirements (Excel add-in solver).

Individualized mineral feed mixtures or supplementary feed mixtures are used in pig feeding. In this way, specific supply gaps can be closed, which usually arise in the area of amino acid supply and phosphorus and calcium supply due to the main feed components. The composition of individual mineral or supplementary feed mixtures therefore depends on the remaining ration. To avoid additional restrictions for the DSS, specifying individual mineral or supplementary feed mixtures as components in the Feedstuff table should be discouraged (see Appendix, Table A1). Instead, the DSS uses standardized mineral or supplementary feed mixtures and allows selective supplementation with special components such as mono and dicalcium phosphate as well as calcium carbonate. Due to the lack of price information, a comparable strategy for individual amino acids is currently impossible. In contrast to the norm, the resulting pig rations are based on a standardized mineral feed that has been modified by adding the aforementioned special components. In this way, the DSS independently defines individual mineral and supplementary feed mixtures and can compensate for changes in the remaining feed ration.

Notably, in high-performance dairy farming, a situation exists in which insufficient energy and/or nXP is fed to cows, resulting in a violation of model restrictions and thus an infeasible solution. However, a feasible solution is a precondition for determining the substitution value of a non-market feed. Although slack variables for “energy deficit” and “nXP deficit” can help bypass this issue, penalty costs are incurred. Due to a lack of knowledge, the amount of these penalty costs could only be evaluated subjectively, which may impact the substitution value of lupine in the high-performance segment of the dairy cow (€0 t^{-1} at 35 kg milk per day). Therefore, an objective evaluation of penalty costs must include all costs that occur due to energy or nXP deficiency, such as those caused by performance reduction, weight loss, animal health, and fertility. However, the objective assessment of penalty costs can lead to an independent research question concerning dairy farming: which costs are caused by a ration-induced undersupply of energy or nXP?

After a comprehensive examination of the application and methodology, the study's findings can be addressed. The market price of €270 t^{-1} for white lupin (from 12/2021; current market prices not available) is considerably below the substitution value (from €0 t^{-1} to €557 t^{-1}) in many areas of application. From a livestock farming perspective, specific demand for white lupins on the market will be beneficial, even if it results in a price increase up to the substitution value. However, the fact that this demand does not exist at present indicates that many livestock farmers misjudge the actual feed value of white lupin. At this point, the different values of white lupin based on the various combinations of animal species, performance, and production processes should be reconsidered. Because substitution values were only determined for a small subset of these combinations in this study, additional combinations should be considered to precisely investigate white lupin valuation. The study's findings already demonstrate, however, that white lupin's very variable nutritional content affects its substitution value. Samples from crop years 2019, 2021, and 2022 resulted in very different substitution values. Within pig fattening, for example, these values varied from €464 t^{-1} to €540 t^{-1}, suggesting the need for sampling lots when determining substitution values. Literature data on ingredients should not be relied upon. For the retail sector, this means that a quality-based pricing system, such as for wheat or rapeseed, is necessary. The results indicate that the achievable substitution values, which simultaneously represent the maximum purchase price of white lupin, are insufficient to exceed the producers' profitability threshold. This situation can only be overcome by subsidization, for example, through AES. If such subsidies are aimed at grain legumes or legumes in general, the production processes concerned become competitive. In the Bavarian case considered, white lupins only make economic sense for producers at prices above €515 t^{-1}, but since the current market price is well below this, soybean cultivation dominates in the direct economic comparison. However, some livestock production processes could achieve substitution values above €515 t^{-1} and in parallel, not every location is suitable for soybean production. In these regions, livestock farmers should at least consider growing white lupins as feed.

Using a practical example, this study illustrates the increasing difficulty of producers and customers agreeing on prices for novel feedstuffs. Nonetheless, the proposed method can assist in overcoming this barrier. Given its effectiveness as a valuable tool for potential buyers of novel feedstuffs to identify upper price limits, the proposed DSS should be used and is available on request from the authors. Regarding white lupin, this tool has demonstrated that its value as a feed markedly exceeds the sparse market price data available. The price situation also results in only small quantities being offered on the market, which in turn makes it difficult to establish a targeted demand for white lupins. Hopefully, the detected discrepancy between the market price and actual value of white lupin as animal feed will lead to an increased demand for white lupins and thus promote local cultivation.

Overall, society can benefit from the accurate identification of the value of novel feedstuffs, as this potentially contributes to diversified land use and more economically efficient livestock production. For the white lupin studied, the supply of domestic protein feed could be increased.

Appendix

Table A1: Feedstuff table (excerpt)

		Lupin_TD_2019	Lupin_TD_2021	Lupin_TD_2022	Wheat	Soybean meal 44%XP	… further feedstuffs	Grass silage	Maize silage
Price	**€/dt FM**	**?**	**?**	**?**	**31**	**66,2**			
DM-original	g/kg FM	915	901	897	880	880		350	350
Ingredients for pig feeding									
DM-standard		880.0	880.0	880.0	880.0	880.0			
ME	MJ / kg Dry-feed	13.9	13.9	13.8	13.7	13.1			
XP	g/kg Dry-feed	376.6	293.9	282.5	121.0	440.0			
Lys	g/kg Dry-feed	18.1	15.9	15.1	3.4	26.9			
Lys pcv	g/kg Dry-feed	14.8	13.0	12.4	2.4	23.4			
Crude fiber	g/kg Dry-feed	103.8	118.8	127.6	26.0	60.0			
Ca	g/kg Dry-feed	2.5	2.9	2.5	0.6	2.7			
dP	g/kg Dry-feed	2.2	1.6	2.2	2.2	2.2			
dP Phytase	g/kg Dry-feed	2.9	2.1	2.9	2.2	4.0			
Crude fat	g/kg Dry-feed	66.9	81.4	79.8	18.0	12.0			
Ingredients for cattle feeding									
Crude fiber	g/kg DM	118.0	135.0	145.0	30.0	68.0		256.0	195.0
aNDF	g/kg DM							515.0	485.0
Crude protein	g/kg DM	428.0	334.0	321.0	137.0	500.0		165.0	82.0
nXP	g/kg DM	261.0	206.0	203.0	170.0	291.0		136.0	134.0
Nel	MJ / kg DM	9.2	9.2	9.2	8.5	8.6		6.0	6.7
Crude fat	g/kg DM	76.0	92.5	90.7	20.0	14.0		38.0	33.0
RNB	g/kg DM	26.7	20.5	18.9	−5.0	34.0		5.0	−8.0

Remarks: DM = dry matter; ME = metabolizable energy; XP = Crude protein; Lys = lysine; pcv = praecaecal digestible; Ca = calcium; dP = digestible phosphate; aNDF = amylase neutral detergent fibre; nXP = usable crude protein; Nel = net-energy lactation; RNB = rumen nitrogen balance.

Table A2: Input interface Dairy Cow

1. Farm-specific data for dairy farming, including the forage ration

a) Animal and performance-related information

	Live weight cow	750	kg
	Milk output per day	30	kg
	--> Milk fat	4,0%	
	--> Milk protein	3,6%	
=	Daily energy requirement	141,1	MJ NEL (Calculation according to "Gruber Futterwerttabelle", Tab. 17)
=	Daily protein requirement	3160	g nXP (Calculation according to "Gruber Futterwerttabelle", Tab. 17)

b) Farm-specific information on forage ration (a maximum of three components is possible, see table "Feedstuff")

Maximum daily DM intake:	3%	of live weight	-->	22,5	kg/day
--> roughage content	66%		-->	14,9	kg/day
|---> 01. Component:	**Grass silage**	50%	DM share in forage		
|---> 02. Component:	**Maize silage**	50%	DM share in forage		
|---> 03. Component:		0%	DM share in forage		

Notice: OK - forage components equal to 100%.
If names have been changed in the "Feedstuff" worksheet, please select them again via dropdown.

c) Other ration requirements

Crude fiber	>=	16,0%	of total DM		
aNDF	>=	28,0%	of roughage DM		
Crude fat	<=	4,5%	of total DM		
Rumen nitrogen balance		-10	to	10	g per day ration

2. Selection of potentially suitable feeds

a) Components for which a substitution value is calculated

		DM max. [g/Day]	% max. in concentrate mix
|---> 1. Component:	Lupin_TD_2019	3500	45%
|---> 2. Component:			

Set price corridor:

Upper bound: 40 €/dt fresh matter (FM)
Lower bound: 50 €/dt FM

Notice: If empty --> no limits

Notice: Componets 1 and 2 must not be selected again in section "b".
If names have been changed in the "Feedstuff" worksheet, please select them again via dropdown.

b) Components with known market value:

		DM max. [g/Day]	% max. in concentrate mix
|---> 3. Component:	Soybean extraction meal 44%X		
|---> 4. Component:	Rapeseed extraction meal		
|---> 5. Component:	Rapeseed cake 8%XL		
|---> 6. Component:	Barley		
|---> 7. Component:	Wheat		
|---> 8. Component:	Soybean		
|---> 9. Component:	Corn		
|---> 10. Component:	Molasses		
|---> 11. Component:	Dairy feed mix III 18%XP		
|---> 12. Component:	Soybean extraction meal 48%X		
|---> 13. Component:	Propylenglycol		
|---> 14. Component:	Triticale		
|---> 15. Component:	Sugar beet chips		

Notice: If empty --> no limits

Notice: Select as many components as reasonable/possible.
If names have been changed in the "Feedstuff" worksheet, please select them again via dropdown.

Table A3: Additional output for dairy cows (according to the input of Table A2)

Ration composition

		Set price for: Lupin_TD_2019 and 'empty' in € per 100 kg FM										
		40	41	42	43	44	45	46	47	48	49	50
Grass silage	kg FM/Day	21,21	21,21	21,21	21,21	21,21	21,21	21,21	21,21	21,21	21,21	21,21
Maize silage	kg FM/Day	21,21	21,21	21,21	21,21	21,21	21,21	21,21	21,21	21,21	21,21	21,21
	kg FM/Day											
Lupin_TD_2019	kg FM/Day	2,25	2,25	2,25	2,25	2,25	1,64	1,64	1,64	1,64	1,64	
	kg FM/Day											
Soybean extraction ı	kg FM/Day											
Rapeseed extraction	kg FM/Day											1,96
Rapeseed cake 8%XL	kg FM/Day											
Barley	kg FM/Day	4,29	4,29	4,29	4,29	4,29	5,28	5,28	5,28	5,28	5,28	4,95
Wheat	kg FM/Day											
Soybean	kg FM/Day											
Corn	kg FM/Day											
Molasses	kg FM/Day											
Dairy feed mix III 18'	kg FM/Day											
Soybean extraction ı	kg FM/Day											
Propylenglycol	kg FM/Day											
Triticale	kg FM/Day											
Sugar beet chips	kg FM/Day											
Ration costs (without forage)	€/Day	2,06	2,08	2,10	2,12	2,15	2,17	2,18	2,20	2,22	2,23	2,24

Ration parameters

			Set price for: Lupin_TD_2019 and 'empty' in € per 100 kg FM										
		Target value	40	41	42	43	44	45	46	47	48	49	50
Daily DM intake	kg	22,5 >=	20,68	20,68	20,68	20,68	20,68	21,00	21,00	21,00	21,00	21,00	20,96
Daily energy requirement	MJ NEL	141,1 <=	144,14	144,14	144,14	144,14	144,14	146,21	146,21	146,21	146,21	146,21	142,52
Daily protein requirement	g nXP	3160 <=	3160	3160	3160	3160	3160	3160	3160	3160	3160	3160	3160
Crude fiber content in the total ration	%	16,0% <=	18,3%	18,3%	18,3%	18,3%	18,3%	17,9%	17,9%	17,9%	17,9%	17,9%	18,2%
aNDF content in roughage	%	28,0% <=	35,9%	35,9%	35,9%	35,9%	35,9%	35,3%	35,3%	35,3%	35,3%	35,3%	35,4%
Crude fat content in the total ration	%	4,5% >=	3,7%	3,7%	3,7%	3,7%	3,7%	3,6%	3,6%	3,6%	3,6%	3,6%	3,3%
Min. RNB in the total ration	g	-10 <=	10	10	10	10	10	-10	-10	-10	-10	-10	-10
Max. RNB in the total ratoin	g	10 >=	10	10	10	10	10	-10	-10	-10	-10	-10	-10

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