Hybrid Crop-Livestock Systems as a Potential Solution to Sustainable Intensification of Agriculture

MSc. Thesis, Plant Production Systems

Kartik C Kamath
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Name Student:	Kartik C Kamath
Registration Number:	1053400
Study:	*MSc Biobased Sciences – Specialization Biomass Production and Carbon Capture*
Chair group:	*Plant Production Systems (PPS)*
Code Number:	*PPS80436*
Date	*April 2023*
Supervisors:	*dr.ir.ing. AGT (Tom) Schut*
	dr.ir. GWJ (Gerrie) van de Ven
Examiners:	*prof.dr.ir. MK (Martin) van Ittersum*

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Summary

The specialisation and intensification of agricultural systems has brought to fore the pressing need to make them more sustainable. Organic agriculture is seen as a sustainable option, but evidence shows that it has a sizeable relative yield gap especially considering the extra land required to grow legumes to fix nitrogen. Integration of crop and livestock farming, known as integrated crop-livestock systems (ICLS) is also seen as a way to improve resource use efficiencies of the system. This thesis compared the yield and environmental performance of a combination of organic feed production and conventional food production (hybrid ICLS), to a fully organic ICLS and a fully conventional ICLS. The number of people whose energy requirements can be met from dairy animal products from a fixed herd size of 106 cows, on an organic and a conventional dairy farm was used as a starting point. Using linear optimisation, the minimum area of land required to meet the energy and protein requirements of the dairy cattle and the consumption requirements of a set of food crops, by humans was determined. The systems were constrained on the amount and sources of N to meet the requirements of food and feed crops. These were to be met by the N returned in the form of manure and crop residues and N inputs from mineral fertilizer, deposition and N fixed in the residues by food and feed legumes and lucerne, grown as a cut and carry fertilizer. The systems were then compared based on the number of people that could be sustained per hectare and the number of animals that could be sustained and the milk production per hectare of feed crops, the mineral fertilizer use per hectare, the N surpluses per hectare and the output/input (O/I) ratios. The hybrid and the conventional ICLS, could both sustain twice as many people as the organic ICLS. The hybrid ICLS produced 18% (13 ton FPCM ha^{-1}) more milk per hectare of feed crops than the organic ICLS (11 ton FPCM ha^{-1}) but 8% less than that in the conventional ICLS (14 ton FPCM ha^{-1}). The hybrid ICLS also used 16% (46 kg mineral N ha^{-1}) less mineral fertilizer than the conventional ICLS (55 kg mineral N ha^{-1}). Among the three systems, the hybrid ICLS had the highest O/I ratio of 0.72 followed by 0.63 for the conventional ICLS and 0.28 for the organic ICLS. In summary, this study shows that there is a synergistic effect of such a hybrid ICLS management system and has potential as a means to the sustainable intensification of agriculture.

Keywords: ICLS, hybrid management, linear optimisation, dairy farming

Contents

1. Introduction

Between 1870 and 1910, European agriculture was transformed in many ways leading to the first 'green revolution'. A number of innovations in fertilizer production and advancing knowledge in soil chemistry led to a rapid increase in mineral fertilizer supply in the years after 1870. This led to a significant drop in prices and a proportional increase in its consumption. The adoption of feed concentrates also drove the intensification of livestock farming in these regions. Additionally, the development of superior crop varieties, improvements in agricultural implements and increased mechanisation along with an increase in agricultural and labour productivities played a pivotal role in this transformation (Van Zanden, 1991). With further modernisation and intensification after 1950, European agriculture became more specialised, and the number of mixed crop-livestock farms declined markedly after 1970. This specialisation was driven by the low product prices due to market globalisation, the post-war output based subsidies of the Common Agricultural Policy (CAP) and the decreasing availability of labour during these years (Ryschawy et al., 2013).

In recent years, however, the environmental impacts of this intensification and specialisation have become increasingly evident. There is a pressing need to make our agricultural systems more sustainable *i.e.*, such that "its exploitation [of an agricultural system] does not degrade the quality of water and soil resources" and the "current management practices do not affect the productivity and viability of the system in the future" (Fereres & Villalobos, 2016). Heavy dependence on external nutrient and crop protection inputs lead to large environmental footprints[1] from production processes and their use on-farm (Skowrońska & Filipek, 2014). This includes considerable nutrient losses to water bodies and to the atmosphere through volatilisation from their on-farm use. This has direct consequences on regional biodiversity. Further, transport of inputs over large distances also contribute to the environmental footprint of food systems[2].

As a substantial part of modern agriculture, dairy farming is not bereft of these issues (Egas et al., 2021). Dairy farming systems emit large amounts of greenhouse gases (GHGs) and nitrogen as a result of enteric fermentation, manure storage and the on-field application of manure and synthetic fertilizers, fossil fuel consumption and external feed production. In addition, a large part of their feed is imported from the Americas bringing the sustainability of the sector into question (Díaz de Otálora et al., 2022). As a result, various agricultural policies *e.g.*, the CAP and the EU Nitrate Directive, are putting pressure on dairy farmers to make milk production economically and environmentally sustainable (Hennessy et al., 2020). These are operationalised through specific goals to monitor and reduce greenhouse gas emissions and reducing dependence on chemical inputs by efficiently managing natural resources. Further, best environmental management practices are also being prescribed and promoted (The European Commission, 2018), to close the gaps in the yield and environmental performances of experimental farms and actual farms.

It is in this context that, circular agriculture has become a burgeoning area of research. The idea of circular agriculture is to optimise the use of resources like mineral fertilisers, crop protection products, land, and energy to reduce the pressure on the environment, nature and climate while still obtaining good yields (Muscat et al., 2021). To quantitatively evaluate the circularity of systems, their nutrient

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[1] The environmental or ecological footprint can be defined as "the impact of human activities measured in terms of the area of biologically productive land and water required to produce the goods consumed and to assimilate the wastes generated" (*Ecological Footprint*, 2020).

[2] All the processes and infrastructure involved in feeding a population (Wilkins & Eames-Sheavly, 2001).

balances (of nitrogen and phosphorous) have been established as important indicators (Zhang et al., 2020) as they help delineate the inputs, outputs and addition/removal to the stocks of the systems.

1.1. A search for more sustainable forms of agriculture

1.1.1. Organic agriculture

In order to distinguish potentially more sustainable forms of agriculture, an overwhelming variety of labels and classifications of agricultural strategies (*e.g.*, sustainable intensification and agroecology) and systems (*e.g.*, organic and conservation agriculture) have been spawned (Sumberg & Giller, 2022). Among these 'varieties' of agricultural systems, organic agriculture (OA) is touted to be the answer to making agriculture more circular and sustainable in light of its independence of synthetic inputs like mineral fertilisers and crop protection products. One of the main features of organic agriculture is that it has longer crop rotations than conventional agriculture. Crop rotations are principally a means to control pests, weeds, and diseases by disrupting their natural cycles by alternating a variety of crops in space and time. It can also be aimed at balancing nutrient use, maintaining, and restoring soil fertility. For instance, cultivating legumes to fix nitrogen into the soil is another characteristic feature of crop rotations in OA. While this practice is not unique to OA and has long been part of agriculture, the advent of synthetic fertilisers and crop protection inputs like herbicides, fungicides, and insecticides etc., has lowered the significance of crop rotations in conventional agriculture and the decisions relating to crop sequences are more market driven. Since organic agriculture, by definition, prohibits the use of such synthetic inputs, there is a considerable difference between the crop rotations used in the two systems of management. This difference mainly stems from the reliance on legumes to fix N in the soil (Mudgal et al., 2010).

It is clear that OA has a positive influence on biodiversity and soils tend to have higher soil organic carbon content (Seufert & Ramankutty, 2017), but it faces criticism for its lower productivity in comparison to conventional agriculture (Connor, 2021; Kirchmann, 2021). Recent evidence establishes that yields of organic crops are, on an average, 19-25% lower than that from conventional management (Seufert, 2019). However, proponents of OA highlight the potential for yield improvement and the need for more targeted research (e.g., more targeted breeding programs and variety selection protocols tailored to organic conditions; Dupuy, 2012) and extension focused on best practices that are not currently used by most farmers (Seufert & Ramankutty, 2017). Even so, in addition to the lower yields, organic systems need to cultivate legumes to source their nitrogen through Biological Nitrogen Fixation (BNF) and often, studies do not account for this additional land requirement when comparing relative yields. An experimental organic farm in Kollumerwaard of the Netherlands called Planty Organic, showed that the corrected yield taking the additional land requirement to cultivate cut and carry fertilisers into account further reduced the yield per hectare by about 17% (Van Der Burgt & Rietema, 2018).

Although the European Union's 'organic action plan' (*European Green Deal: Commission Presents Actions to Boost Organic Production*, 2021) was voted against, efforts are being made to incentivise organic production and consumption, with member states designing their own national organic strategies (Foote, 2022; "Organic Farming Grows If the Market Grows," 2022). In 2020, 9.1% of the total utilised agricultural area was used for organic farming in the European Union (*Organic Farming Statistics*, 2022).

1.1.2. Integration of Crop-Livestock Systems

Integrated crop-livestock systems (ICLS) are keenly being explored as a means to close nutrient cycles in agricultural systems and reduce dependence on external inputs. ICLSs synergize arable crop and livestock production to make systems more resource-use efficient (Regan et al., 2017), conserving natural (water and air) and non-renewable resources (phosphorous and fossil energy), while providing ecosystem services (facilitating pollination, improving soil fertility and pest control) and halt biodiversity losses (Peyraud et al., 2014). However, the advantages of ICLSs are highly context specific and depend on the level of integration (Martin et al., 2016; Regan et al., 2017). Martin et al. (2016), identify three levels of integration beyond the farm level: local coexistence, complementarity, and synergy. Local coexistence refers to the exchange of materials (*viz.*, feed, straw and/or manure) between farms through third party economic organisations, without the coordination of individual farmers. Complementarity refers to the direct exchange of materials between collaborating farmers and the temporal coordination of their activities in response to the supply and demand of materials. Synergy involves spatial coordination in addition to the temporal coordination of activities between collaborating farmers *i.e.*, resources such as land are also shared between collaborating farmers. This may include the introduction of forage crops, grasslands etc., in the crop rotations or stubble and sacrificial grazing. Apart from material exchange, the latter two forms of integration facilitate knowledge and labour exchange as well. The level of integration may be determined by the proximity of the collaborating farms.

Grasslands have been established to be good stores of carbon and nitrogen due to their continuous ground cover and the absence of tillage. However, intensification of dairy farming and the increased use of energy-rich feed crops such as grains and whole plant silages are among the factors that have led to a decline in grassland areas, over the years (Taube et al., 2014). The ploughing of these grasslands mineralises part of the carbon stored in the topsoil, decoupling carbon from nitrogen, leading to the emission of GHGs (*e.g.*, CO_2 and N_2O) and a reduction of soil organic carbon content. To counteract this, the incorporations of leys or rotations with short-term grassland periods with minimum tillage measures have been suggested as an alternative management strategy (Struck et al., 2020). The following crops of the rotation can then benefit from this newly mineralised nitrogen (Nevens & Reheul, 2002). These leys are often mixed swards that include legumes such as red or white clover. This helps increase N supply to the system, through BNF, reducing the need for mineral fertilizer and also boosts animal productivity when incorporated into feed mixtures (Johansen et al., 2017). Further, the relative yield gap of grass-clover dry matter productivity is less than that for arable crops. This is because the clover proportion of the sward varies inversely with N input and thereby fixes more N to make up for the low input (Oberson et al., 2013).

Connor (2022) conducted a study in Swedish crop-livestock systems where average yields of grain and fodder crops in organic and conventional systems were expressed in Human Metabolizable Energy (HME) and Ruminant Metabolizable Energy (RME). This was used to maximise the amount of HME obtained from milk alone or that from milk and grain. The study showed that, depending on the region, dairy productivity under organic management can be comparable to that under conventional management. This convergence of relative yield, however, primarily occurred in the colder regions of northern Sweden where growing seasons were shorter, crop choices were limited (largely restricted to pastures) and yield responses to nitrogen supply were lower than in the south, leading to lower conventional grain yields. Therefore, until OA is able to bridge its relative yield gap with conventional agriculture, a more context specific, place-based adoption of OA is required.

In this context, this thesis seeks to assess if a combination of organic feed production and conventional production of food crops alleviates the environmental effects of the extreme specialisation and intensification of agriculture without suffering significant yield losses. Feed is chosen to be produced organically in the hybrid system because a lower reduction in productivity, compared to a fully conventional ICLS, is expected than if food were produced organically. However, strict regulations of OA currently pose regulatory challenges for organic certification of such hybrid management.

2. Research Question

This thesis aims to assess the environmental performance and productivity of a hybrid ICLS where livestock kept for dairy production is managed organically, and the cropping component is managed conventionally. The intention is to see if such a hybrid management of crop and livestock reduces the dependence on synthetic nutrient sources and improves circularity.

To evaluate and compare the hybrid ICLS, the following three management types for food and feed crops will be considered:

1. Organically managed food crops coupled with organically managed feed crops (Organic ICLS).
2. Conventionally managed food crops coupled with conventionally managed feed crops (Conventional ICLS).
3. Conventionally managed food crops coupled with organically managed feed crops (Hybrid ICLS).

Thus, the research question:

How does the productivity and nutrient cycling performance of a hybrid ICLS compare with that of an organic ICLS and a conventionally managed ICLS in northern Germany?

will be answered through the sub-questions:

1. *How do the three management types differ in the amount of land required to meet current human diets?*
2. *What is the nitrogen Output/Input (O/I) ratio of the three management types?*
3. *What regulatory hurdles exist for the hybrid system and how can they be overcome?*

It is hypothesised that hybrid systems are more productive than organic systems but with a lower environmental impact than conventional systems due to a lower use of synthetic inputs.

3. Methods

The methodology followed to assess the productivity and environmental performance of a Hybrid ICLS in comparison to a conventional ICLS and an Organic ICLS is described in this section. A dairy herd size of 106 cows, based on an existing dairy farm, "the Lindhof" located in Kiel, Germany, was used as a starting point (*Lindhof Test Farm*, 2022). The number of people whose milk and meat requirements, based on current consumption patterns could be met was calculated. Along with milk and meat production, manure production was also estimated. This was also done for a hypothetical conventional dairy farm with the same herd size, based on averages from literature. The only difference was in the milk production per cow and its liveweight. These calculations are presented in Section 3.1 and the parameters used in this analysis along with their units and values are presented in Appendix A.

For the next step, a set of food and feed crops were considered for the sake of this analysis. Their organic and conventional yields, annual human consumption (for food crops) and VEM[3] and DVE[4] contents (for feed crops) were collated. Further, their N uptake or N fixation (in case of legumes), dry matter fractions were collated, and the N in crop residues were estimated based on factors like their N harvest indices, protein contents and N uptake. This data is presented in Sections 3.5 and 3.6 and their sources and the intermediary data used to arrive at this data is presented in Appendix B.

The three ICLS management types were thus compared based on the area of land needed to meet the demands of the people that can be sustained from the dairy farm and the nutritional requirements of the dairy herd. Further the required N available for uptake also had to be met by N return flows of manure and crop residues and N inputs of mineral fertilizer, deposition and BNF. The components of the N return flows and inputs are described in Section 3.6. When the model that is described in Section 3.7 was run preliminarily, it was seen that there was a considerable N deficit and for this reason, Lucerne was introduced as a separate rotation to be used as a cut & carry fertiliser as in van der Burgt et al. (2021) to close this deficit. The yield data for lucerne was taken from the Agriculture and Horticulture Development Board (ahdb.org.uk) and the nitrogen concentration was considered to be similar to data reported in van der Burgt et al. (2018, 2021). Further the N fixation and partitioning between above- and below-ground parts of the crop were based on Anglade et al. (2015).

A linear optimisation model was then made for each of the management types, described in Section 2, where the amount of N available through manure, the N uptake of the crops, the current human demands of each of the crops considered, and the DVE and VEM requirements of the cattle were used as constraints to determine the minimum amount of land required. The land required and the N balance of each of the management types were then compared, to answer the research questions.

The following sections describes the calculations made in the process, using R, and the formulation of the linear programming (LP) model that was implemented in GAMS. Appendix C presents the mathematical formulation of the LP model.

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[3] VEM (*Voeder Eenheid Melk* or Feed Unit Milk) is a dimensionless parameter that relates the net energy for lactation available from a feed to that available from 1 kg of standardised barley (1000 VEM = 6.9 MJ NEL from 1 kg of barley)

[4] DVE (*Darm Verteerbaar Eiwit* or Gut Digestible Protein) is the microbially produced protein that is available for digestion in the small intestine of the cow.

3.1. Capacity of the Lindhof farm to meet milk and meat requirements

3.1.1. Energy and protein supply from milk and meat

The milk production in kg energy corrected milk (ECM), in organic and conventional dairy farms was taken from Loges et al. (2019) and Lehrke & Futterkamp, (2021), respectively. ECM is milk that is normalised to have 3.2% protein and 3.5% fat. This was converted to fat and protein corrected milk (FPCM) using the standard equation from the International Dairy Foundation, (2015) presented below. FPCM is milk that is normalised to have 3.3% protein, 4% fat with an energy content of 0.7576 Mcal kg^{-1} or 3.17 MJ kg^{-1}.

$$FPCM = Milk\ * (0.1226 * Fat\% + 0.0776 * Protein\% + 0.2534) \qquad \text{[kg FPCM]}$$

where both Milk and FPCM are in kg.

Thus, the total milk produced on farm and its energy and protein contents were calculated as:

$$Total\ FPCM\ production = No.of\ cows *\ FPCM\ productivity \qquad \text{[kg FPCM year}^{-1}\text{]}$$

$$Energy\ supply\ FPCM = Energy\ content\ FPCM * Total\ FPCM\ production \quad \text{[MJ year}^{-1}\text{]}$$

$$Protein\ supply\ FPCM = Protein\ content\ FPCM * Total\ FPCM\ production \quad \text{[kg protein year}^{-1}\text{]}$$

To calculate the annual amount of meat that can be produced from the dairy herd, a number of factors were considered. The proportion of the live animal weight that results in the unchilled carcass, after the head, hide and internal organs have been removed, is termed the dressing percentage. As a general rule, beef cattle have a dressing percentage of 62-64% and 56-60% for dairy cattle. Further, the carcass is processed into cuts before being sold. All told, the trimmed, chilled and de-boned cuts amount to approximately 42% of the cow's live weight (LW; Holland et al., 2014). This was expressed as a fraction of unit LW that results in boneless meat from these cows, hereafter referred to as beef. Furthermore, dairy cows have a lifespan of an average of six years after which they are culled (De Vries & Marcondes, 2020). Beef contains 7.5 MJ of energy and 20 g of protein per 100 g (NEVO, n.d.). Thus, the annual energy and protein supply from beef production was calculated as follows:

$$Production\ beef = \frac{No.of\ cows * LW\ cow * Fraction\ beef}{Lifespan\ dairy\ cow} \qquad \text{[kg beef year}^{-1}\text{]}$$

$$Energy\ supply\ beef = Energy\ content\ beef * Production\ beef \qquad \text{[MJ year}^{-1}\text{]}$$

$$Protein\ supply\ beef = Protein\ content\ beef * Production\ beef \qquad \text{[kg protein year}^{-1}\text{]}$$

The Lindhof farm has a spring-calving herd (Loges R et al., 2019) of which only 25% of calves are retained to replace and expand the herd and 25% are fattened for their veal (*Lindhof Test Farm*, 2022). The remaining 50% of the calves were assumed to be culled shortly after birth. This was considered to be a reasonable assumption as it found agreement in literature that 230 of 325 Danish dairy farmers, culled approximately 59% of their jersey bull calves because they could neither sell them to conventional farmers nor to organic farmers (Nielsen & Thamsborg, 2002). In this analysis, the expansion of the herd was not considered *i.e.*, the herd size was assumed to be maintained at 106 cows.

> "Veal is defined as cattle of any dairy breed or dairy crossbreed dressing no more than 190 kg (419 lbs). This converts to a live weight of roughly 349 kg (769 lbs.), which is reached at approximately eight months of age." (Veal farmers of Ontario, 2021)

While there are different types of veal meats depending on the feeding regime (white, rose veal or free-range veal) and the age at which the calves are culled, according to the definition above, the dressing percentage is approximately 54%. A relatively old study, by Brekke & Wellington, (1969), shows a boneless meat yield of 43% across three different slaughter weights. Thus, for the sake of consistency and due to reliability on more recent studies, the same meat yield percentage of 42% from beef was taken[5]. Veal contains 8.9 MJ of energy and 19 g of protein per 100 g (NEVO, n.d.). Therefore, the annual supply of energy and protein from veal production was calculated as:

$$Production\ veal\ = No. of\ cows * Calving\ frequency * LW\ calf * Fraction\ veal * fraction\ calves\ retained\ for\ fattening$$ [kg veal year^{-1}]

$$Energy\ supply\ veal = Energy\ content\ veal * Production\ veal$$ [MJ year^{-1}]

$$Protein\ supply\ veal = Protein\ content\ veal * Production\ veal$$ [kg protein year^{-1}]

3.1.2. Energy and protein demand from milk and meat

The average daily milk and milk product consumption per person was taken from Bosland (2022) where various losses along the value chain were considered. This was based on milk with 4.4% fat and 3.4% protein. To calculate the annual milk demand, the daily consumption was corrected for its fat and protein concentration using the formula from the International Dairy Foundation, (2015) and multiplied by 365[6]:

$$\text{Demand FPCM} = Daily\ consumption\ milk * 365 * ((0.1226 * fat\%) + (0.0776 * protein\ \%) + 0.2534)$$ [kg FPCM person^{-1} year^{-1}]

Among the variety of meats consumed, beef and veal demands were obtained from the average carcass weights consumed per person over 5 years in the Netherlands (Dagevos et al., 2020). Dutch data was used under the assumption that the meat consumption patterns aren't significantly different from those in Germany. This carcass weight was then converted to beef and veal yields:

$$Demand\ beef\ = \frac{Fraction\ beef}{Dressing\ fraction\ cow} * Annual\ consumption\ beef\ carcass$$ [kg beef person^{-1} year^{-1}]

$$Demand\ veal\ = \frac{Fraction\ veal}{Dressing\ fraction\ calf} * Annual\ consumption\ veal\ carcass$$ [kg veal person^{-1} year^{-1}]

Where *Fraction beef* and *Fraction veal* are the boneless beef and veal meat yields of cows per unit LW.

3.1.3. Capacity of the dairy farm to meet energy and protein requirements from dairy animal products

From this data on the milk and meat (beef and veal) demands, and their supply from the dairy farm, the number of people whose energy and protein requirements could be met from the consumption of these dairy animal products was calculated.

$$Energy\ demand\ dairy\ animal\ products = (Demand\ FPCM * Energy\ content\ FPCM) + (Demand\ beef * Energy\ content\ beef) + (Demand\ veal * Energy\ content\ veal)$$ [MJ person^{-1} year^{-1}]

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[5] The boneless meat yield is referred to as veal

[6] Due to a calculation error where *fat%* and *protein%* were expressed as fractions instead of percentages, the calculated *Demand FPCM* was 72 kg FPCM person^{-1} year^{-1} instead of 290 kg FPCM person^{-1} year^{-1}

$$Protein\ demand\ dairy\ animal\ products = (Demand\ FPCM * Protein\ content\ FPCM) + (Demand\ beef * Protein\ content\ beef) + (Demand\ veal * Protein\ content\ veal)$$

[kg protein person^{-1} year^{-1}]

$$Energy\ supply\ dairy\ animal\ products = Energy\ supply\ FPCM + Energy\ supply\ beef + Energy\ \text{supply veal}$$

[MJ person^{-1} year^{-1}]

$$Protein\ supply\ dairy\ animal\ products = Protein\ supply\ FPCM + Protein\ supply\ beef + Protein\ supply\ veal$$

[MJ person^{-1} year^{-1}]

$$No.of\ people\ sustained\ based\ on\ energy\ requirements = \frac{Energy\ supply\ dairy\ animal\ products}{Energy\ demand\ dairy\ animal\ products}$$

[# people]

$$No.of\ people\ sustained\ based\ on\ protein\ requirements = \frac{Protein\ supply\ dairy\ animal\ products}{Protein\ demand\ dairy\ animal\ products}$$

[# people]

The *No. of people sustained based on energy requirements* was decided to be chosen as the input parameter to the LP model. While either choice can be justified, meeting calorific requirements may be considered as a more basic need than meeting protein requirements alone. Further, if calorific requirements are met, the shortfall in protein requirements can be compensated by other sources of protein.

The milk, beef and veal production of the dairy farms are shown in Table 1 and the number of people that can be sustained at their current diet, from each of the dairy farms is shown in Table 2. As mentioned earlier, the difference in the data used for the organic and conventional dairy farms are in the liveweights of the cows and their milk production. This is why the milk and beef production are higher in the conventional dairy farm than in the organic dairy farm. The veal production was the same in both, the organic and conventional dairy farms because the weight at which the calves were considered to be culled for veal meat was the same in both the dairy farms.

Table 1: Milk and meat production from organic and conventional dairy farms

	Milk production (kg FPCM year^{-1})	Beef production (kg beef year^{-1})	Veal production (kg veal year^{-1})
Organic dairy farm	681474	3191	3884
Conventional dairy farm	868352	5046	3884

Table 2: Number of people to be sustained by the dairy farm

Organic dairy farm	7351
Conventional dairy farm	8704

3.2. Food requirements

A set of food crops were chosen to be grown based on the current crop production in Germany (Statisches Bundesamt, 2021). It is to be noted that this analysis does not aim to calculate the land requirement for a complete human diet. Rather, it seeks to compare, for a limited diet, the differences in the land requirements across different ICLS management types. Therefore, a set of representative crops from different crop groups currently produced in Germany were chosen, such that major crop groups that are grown in typical specialised systems were covered. The current annual demands per capita of each of these crops were calculated from collated daily demands per capita. These are shown in Table 3.

Table 3: Current food consumption

Crop	Current demand (kg $pers^{-1}$ $year^{-1}$)	Sources
Winter wheat	68.0	(Bosland, 2022)
Barley	7.8	(Bosland, 2022)
Oat	16.4	Based on a standard serving size of 0.5 cups per day
Grain maize	7.6	(Erenstein et al., 2022)
Fava bean	0.9	(Bouchenak & Lamri-Senhadji, 2013)
Field pea	0.9	(Bouchenak & Lamri-Senhadji, 2013)
Potato	68.8	(Bouchenak & Lamri-Senhadji, 2013)
Sugar beet	208.9	(Bosland, 2022)
Winter rapeseed	30.6	(Bosland, 2022)

3.3. Feed requirements

The energy and utilizable protein requirements for dairy cows were estimated using equations from Duinkerken & Spek, (2016) as presented in this section. The VEM requirements for milk production and maintenance, per year were calculated as shown below (Duinkerken & Spek, 2016). The energy requirements are calculated as a function of the live weights of the cows and their FPCM productivities. Calf nutrition was not considered in this analysis. However, since neither of the management types considered calf nutrition requirements, the results are still comparable. The energy requirement is a function of the LW and the amount of milk produced per cow per day which was scaled to include the energy requirements of all cows over the entire year.

$$VEM\ demand = \left(42.4 * LW\ Cow^{0.75} + 442 * \frac{FPCM\ productivity}{365}\right) * \left\{1 + \left(\frac{FPCM\ productivity}{365} - 15\right) * 0.00165\right\} * 365 * No.of\ cows$$

[VEM $year^{-1}$]

Where, *LW Cow* is expressed in kg cow^{-1} and *FPCM productivity* in kg FPCM cow^{-1} $year^{-1}$. The calculations of the protein requirements for maintenance and lactation are shown below (Duinkerken & Spek, 2016). The maintenance energy requirements were calculated as a function of the liveweight of the cows and the lactation protein requirements, as a function of the protein produced in milk, per day. The equation calculates the maintenance requirements of DVE in g DVE day^{-1} cow^{-1}. This was converted to kg DVE $year^{-1}$. The lactation protein requirements were calculated as a function of the protein produced in milk, daily, and scaled to the annual protein requirements of the entire herd in kg DVE $year^{-1}$.

$$DVE\ maintenance = \left(54 + (0.1\ * LW\ Cow)\right) * 365 * 10^{-3} * No.of\ cows$$

[kg DVE $year^{-1}$]

$$Protein\ produced\ in\ milk\ daily = Protein\ content\ FPCM * \left(\frac{Milk\ yield}{365}\right) * 1000$$

[g DVE day^{-1}]

$$DVE\ lactation = (1.396 * Protein\ produced\ in\ milk\ daily + 0.000195 * (Protein\ produced\ in\ milk\ daily)^2) * 365 * 10^{-3} * No.of\ cows$$

[kg DVE year^{-1}]

$$DVE\ total = DVE\ maintenance\ + DVE\ lactation$$

[kg DVE year^{-1}]

The maintenance and lactation energy and protein requirements of the full herd is shown in Table 4.

Table 4: Annual VEM and DVE demands of the full herd.

	VEM demand (MVEM year^{-1})	DVE demand (ton DVE year^{-1})
Organic dairy farm	458	37.70
Conventional dairy farm	610	48.86

The feed crops were also chosen from the cereals grown in Germany along with grass-clover grown as a ley. The VEM and DVE contents of this set of feed crops are shown in Table 5.

Table 5: VEM and DVE contents of feed crops

Feed crops	VEM (kVEM ton^{-1} (DM); from feedtables.com and feedipedia.org)	DVE (kg DVE ton^{-1} (DM); from feedtables.com)
Rye	1180	92
Triticale	1165	92
Silage maize	1049	93
Grass clover	880	89

3.4. Manure production

The amount of N excreted in manure was estimated based on the N and urea contents of the milk using the equation shown below from Šebek et al., (2014). The urea content of the milk was obtained from Smit et al., (2021) and the N content was estimated using the Kjeldahl factor of 6.38 (Maubois & Lorient, 2016).

$$N\ Manure = \left(124 + 1320 * (Urea\ milk * 10^{-2}) + 1.87 * \frac{FPCM\ productivity * Protein\ content\ FPCM * 1000}{365 * 6.38} - 6.9 * \frac{FPCM\ productivity}{365}\right) * 365 * 10^{-6} * No.of\ cows$$

[ton N year^{-1}]

The values obtained are shown in Table 6.

Table 6: Manure production in organic and conventional dairy farms

	Manure N production (kg N year^{-1})
Organic dairy farm	17003
Conventional dairy farm	17521

3.5. Crop rotations

In reality, the design of an appropriate crop rotation is complex and depends on many variables including the agroclimatic conditions, the local market, and economic contexts of the farm. Comprehensive tools to design such rotations *e.g.*, ROTAT, are available. However, this analysis considered example rotations based on crops currently produced in Germany under organic and conventional management, and typical rotations in similar climatic zones of Europe (Mudgal et al., 2010; Statisches Bundesamt, 2021, 2022). It is to be noted that the aim of this analysis is not to prescribe an ideal crop sequence and therefore these example rotations are not optimized perfectly. After preliminary runs of the LP model, the crops in each rotation were reorganised to minimise surplus production of food and feed. Table 8 shows this data for lucerne and other crops and Table 7 shows the final crop rotation used for this analysis.

Table 7: Crop rotations considered for the three management types.

	R1	**R2**	**R3**	**R4**	**R5**
Food crop					
Winter_wheat	0	0	0	0	1/2
Barley	0	2/14	1/5	0	0
Oat	2/7	0	0	0	0
Grain_maize	0	3/14	0	0	0
Fava_bean	0	2/14	0	0	0
Field_pea	1/7	0	1/5	0	0
Potato	0	2/14	1/5	0	0
Sugar_beet	2/7	1/14	0	0	0
Winter_rapeseed	0	0	0	0	1/2
Feed crop					
Rye	0	2/14		0	0
Triticale	0	0	1/5	0	0
Silage_maize	0	0	1/5	0	0
Grass_clover	2/7	2/14	0	0	0
Legume					
Lucerne	0	0	0	1/1	0

Data on conventional yields of the considered crops, in Germany and Netherlands were obtained from various sources including literature and the Global Yield Gap Atlas (https://www.yieldgap.org/). The harvest indices, nitrogen harvest indices, the dry matter percentages and the N requirements were also obtained from various literature sources and databases. These are shown in Table 8 and the sources are presented in Appendix B. The required nitrogen uptake to attain the target yields, for each of the crops were estimated either based on the QUADMOD model (Ten Berge et al., 2000) or were collated from fertilizer recommendations. The equations for the QUADMOD model were used to interpolate the N uptake for a target DM yield and an N dose using the uniroot function in R. These N requirement and fixation values are shown in Table 9. The same N requirements were assumed for both organic and conventional management. The N in residues were calculated either based on the N harvest indices (NHI) and the N uptake or the protein content was converted to the N content using a Kjeldahl factor of 6.25 (Maubois & Lorient, 2016). The equations used in this calculation were either of the following depending on the availability of data:

$$N\ in\ residues_{crop} = \left(1 - NHI_{crop}\right) * N\_uptake_{crop}$$

Or,

$$N\ in\ residues_{crop} = \left(\frac{protein\_content_{crop}}{6.25}\right) * yield_{crop} * 10^3 * \frac{1 - NHI_{crop}}{NHI_{crop}}$$

Or,

$$N\ in\ residues_{crop} = yield_{crop} * DM\_frac_{crop} * \frac{(1 - HI_{crop})}{HI_{crop}} * N\_concentration_{crop\_residue} * 10^3$$

Where protein_content$_{crop}$ is in kg protein per kg DM, HI$_{crop}$ and NHI$_{crop}$ are dimensionless, N_uptake$_{crop}$ is in kg N per hectare, yield$_{crop}$ is in ton DM per hectare, DM_frac is the dry matter fraction in kg DM per kg FM, N_concentration$_{crop\_residue}$ is in kg N per kg DM and N in residues$_{crop}$ is in kg N per hectare. This data for each of the crops considered and their sources are presented in Appendix B.

Of the N fixed by fava beans and field peas, it was assumed that 50% would be available to the succeeding crops (Fuchs, 2020; Islam & Adjesiwor, 2018). The N fixation for grass-clover was estimated based on Thers et al., (2022) where 90% of the N in the shoot of the harvested legume is fixed and 10% of this is transferred to the soil.

Table 8: Food and feed crop yields considered under organic and conventional management along with their dry matter fractions and the N in residues

Crops	Conventional yields (ton FM ha^{-1})	Organic yields (ton FM ha^{-1})	DM fraction (ton DM/ton FM)	N in residues (kg N ha^{-1})
Winter wheat	8.8	6.4	0.87	25
Barley	7.0	4.8	0.83	35
Oat	4.7	4.0	0.88	43
Grain maize	10.1	9.0	0.85	62
Fava bean	4.4	4.0	0.85	33
Field pea	3.3	2.9	0.86	62
Potato	39.8	27.8	0.22	24
Sugar beet	73.1	76.8	0.24	108
Winter rapeseed	3.3	2.7	0.935	107
Rye	4.2	3.2	0.88	19
Triticale	5.4	4.4	0.90	26.6
Silage maize	22.2	19.8	0.68[7]	0.0
Grass clover	50.0	50.0	0.22	343.0
Lucerne	40	36	0.3	360

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[7] The correct value is 0.325.

Table 9: N requirements and N added from fixation for all crops

Crops	N Requirements (kg N ha^{-1} year^{-1})	N fixation (kg N ha^{-1} year^{-1})	References
Winter wheat	79	-	(Ten Berge et al., 2000)
Barley	129	-	(kennisakker.nl)
Oat	141	-	(Tamm, 2003)
Grain maize	195	-	(Ten Berge et al., 2000)
Fava bean	-	219	(Neugschwandtner et al., 2015)
Field pea	-	185	(Fageria, 2014)
Potato	82	-	(Ten Berge et al., 2000)
Sugar beet	171	-	(Kaiser, 2022)
Winter rapeseed	145	-	(grdc.com; Bouchet et al., n.d.)
Rye	85	-	(kennisakker.nl)
Triticale	134	-	(kennisakker.nl)
Silage maize	195	-	(Ten Berge et al., 2000)
Grass clover	-	169	(Thers et al., 2022)
Lucerne	-	230	(Anglade et al., 2015)

3.5.1. Management of crop rotations

The input data used in this analysis are specific to certain management choices and can vary with local climatic and biophysical conditions. However, it is assumed that specific Best Environmental Management Practices (BEMPs) that are tailored to the site in question are followed, and relevant monitoring strategies are used.

The document drafted by the EU delineating these BEMPs, their indicators and benchmarks of excellence, are used as a reference (The European Commission, 2018). The document recommends, with regard to nutrient management that systematic soil testing be done every three years for crops and leys. This is done to maintain a pH within the optimum range of 6.5-7.5 and to budget for nutrients to avoid excess application. Incorporation of legumes in crop rotations, for their ability to fix nitrogen is also advocated especially for low input systems that use only organic inputs or use low amounts of fertilizers. This is however, not recommended in farming systems with peaty soils that are acidic as it adversely affects the mechanisms of BNF. In the case that mineral fertilizers are used, those with lower documented carbon footprints are to be chosen. When urea-based fertilizers are used, those coated with nitrification inhibitors are to be used to minimize N losses (Hennessy et al., 2020). These nitrification inhibitors reduce denitrification and leaching losses by suppressing microbial populations responsible for the conversion of ammonium to nitrite and nitrite to nitrate (Thompson et al., 2021). With regards to manure management, a number of alternatives are described. The manure can be anaerobically digested so that the nitrogen is converted to more bioavailable forms, it can be composted, or shallow injection close to crop roots can be employed to reduce ammonia volatilisation. In this analysis, no composting or anaerobic digestion processes have been considered and thus only the latter alternative of shallow injection is considered.

Similarly, de Ruijter et al., (2010) found that incorporation of crop residues emitted less ammonia than when the residues were left on the surface. Therefore, crop residues are to be incorporated into the soil where possible. For legumes, it has been noted that the presence of the right strains of *Rhizobia* also affect the fixation rate. This might necessitate inoculation to improve N-fixation. Further, inoculation with arbuscular mycorrhizal fungal populations have also been shown to play an important role in improving transfer efficiency of fixed N from legumes to succeeding non-legume crops (Islam

& Adjesiwor, 2018). Therefore, such management decisions may lead to different N return and input rates from the return of residues and cultivation of legumes, respectively, than the data used in this analysis.

3.5.2. Relative yield gap between organic and conventional systems

The relative yield gap between organic and conventional systems has been widely debated. While the consensus is that, in terms of yields alone, the gap is between 20 and 25%, the reduction in productivity due to the additional land required to grow legumes to meet nutrient demands from non-synthetic inputs has also been critiqued. This analysis used relative yield gaps from De Ponti et al. (2012). A yield gap was not considered for grass-clover. A constant yield of 11 ton DM ha^{-1} was considered with an estimated average clover proportion at 0 kg N input and a constant N concentration in the clover and a constant proportion of N fixed and transferred to the soil from Thers et al. (2022). De Ponti et al. (2012) acknowledge that their meta-analysis does not establish firm relationships on yield reducing factors and that organic agriculture depends more on nutrient management through well-designed crop rotations and organic amendments. Seufert (2019) reviews that among yield reductions due to nutrient limitations and disease management, the former is typically more limiting. However, this analysis considers the same N requirements for both organic and conventional management. Therefore, these relative gaps were assumed to be largely due to reductions from pests and diseases.

3.6. N Availability, Fertilisation and Associated Losses

In this analysis, the soil available N was assumed to be at a steady state determined by the N returned in the form of crop residues, manure and N inputs including deposition and mineral fertilizers in case of conventional management. It is generally accepted that the rate of mineralisation of organic matter is determined by the C:N ratio, apart from other factors like residue-soil contact and soil N content. The C:N ratio of residues varies over time and hence also the rate at which it is mineralised. This rate also affects the associated losses. N from mineral and organic sources, like manure, have differences in their bioavailability due to different uptake rates, losses, and rates of decomposition in an agricultural production system. One metric that is used to compare organic N sources with mineral N is the N Fertiliser Replacement Value (NFRV). It is the amount of mineral fertiliser that can be saved per unit amount of an organic N source without suffering a yield loss. This NFRV has been shown to significantly increase with the total N available (Hijbeek et al., 2018). Average NFRVs for crop residues (0.40 kg mineral N/kg residue N) and manure (0.83 kg mineral N/kg manure N), at high and low available N from Hijbeek et al. (2018), were used to estimate the N recirculated within the system (in the form of manure and non-leguminous crop residues) and input through cut and carry fertilizer and other leguminous crop residues. This is however a simplification as, it depends on a variety of factors, such as the crop composition of the rotation, the crop N demand, and its synchronicity with the mineralisation of N in the soil and climatic factors viz., temperature and rainfall.

Furthermore, fertilisers can supply N beyond the years of their application, which is termed the N legacy effect (Vonk et al., 2022). However, Vonk et al. (2022), found no significant correlation between the total N supply and the N uptake in contrast to the findings of Hijbeek et al. (2018) which considered the long term NFRV of organic fertilisers and hence also their legacy effect. The results of Vonk et al., (2022), demonstrate that, considering the legacy effect of mineral fertilisers over a long term, 66% is effectively taken up by the crops in a year. Apart from an NFRV for manure, the losses associated with cattle housing and grazing, and manure storage, for Germany were obtained from Oenema et al. (2007). Therefore, the amount of farmyard manure that would be equivalent to supplying mineral fertilizer is:

$$N\_supply\_manure = uptake\_eff * N\_manure * NFRV\_manure * (1 - N\_manure\_losses)$$

Where uptake_eff is the uptake of mineral fertilisers considering their legacy effect, N_manure is the amount of manure available on-farm, NFRV_manure is the amount of mineral N that the manure N is equivalent to, and N_manure_losses are the losses associated with housing and storage.

A national average of nitrogen deposition of 14.8 kg N/ha for Germany was obtained from Schaap et al., (2017) and also considered as an N input to the system. This N was also considered to be taken up at the same uptake efficiency. The N in the input and return flows that are not taken up partly contribute to maintaining the soil N stock and the remainder is lost. This proportion, however, is not quantified in this analysis.

3.7. Linear optimisation

Having collated this data, a linear optimisation model was formulated per management type, to minimise the land required to grow crops to meet human and cattle demands, with constraints of the availability of N per management type. The main decision variable was the land allocation per rotation and the objective function was to minimise the total land allocated over all rotations. A constraint on food production ensured that enough land was allocated to each of the food crops produced to meet the human demands and similarly enough land was to be allocated to meet the VEM and DVE demands of the dairy herd. Further, an N sufficiency constraint was imposed where the total N demands of food and feed crops were to be met separately (less than or equal to *i.e.*, a surplus was allowed) by a combination of N returned through crop residues, cut and carry fertilizer and manure considering appurtenant NFRVs, uptake efficiencies and manure losses, as described in the previous section. Along with this N inputs to the system included mineral fertilizer and deposition. No mineral fertilizer use was allowed in the organic ICLS; the conventional ICLS used mineral fertilizer to meet the N demands after N from crop residues, cut and carry fertilizer, manure and deposition met part of the total N requirements of a rotation; and the hybrid ICLS used mineral fertilizer to meet only the N demands of the food crops after other N from crop residues, cut and carry fertilizer, manure and deposition met the N requirements of the food crops within a rotation. The redistribution of food and feed crop residues within a rotation was allowed such that the N demands of both food and feed crops could be met with minimum surpluses, in all the ICLS management types. Since the use of mineral fertilizer in the hybrid ICLS was to be defined by the N demands of food crops and the N inputs and returns to food crops from BNF, manure and deposition, the N demand, return and input terms had to be separated for food and feed crops. However, this meant that the N fixed by food and feed legumes could not be exchanged across these crop groups. Thus, for the sake of consistency and fairness of comparison, the N demands and in turn the N sufficiency constraints were separated for food and feed crops in all management types. This formulation is given in Appendix C: Objective function and constraints to the LP model.

A certain amount of surplus food and feed can be produced in each management type. The surplus food can be exported, and the surplus feed used in expansion of the herd. However, to compare the management types, these surpluses were corrected for. Accordingly, the land requirements for crops and lucerne, the mineral N fertilizer use, the O/I ratio and the N surplus per hectare were calculated after discounting these surpluses. The land area required was corrected by reducing the land required to produce the excess amount of food and feed. In the case of feed, the correction for surpluses was based on the VEM production alone. The mineral N fertilizer was corrected by calculating the contribution of fertilizer in meeting the N demands of each rotation and allocating the same share of fertilizer to meet the N demands per rotation after correcting the area for food and feed surpluses. In case of lucerne grown as cut and carry, this too was corrected by maintaining the same share of contribution to meeting all rotations' N demands after correcting for food and feed surpluses. To calculate the O/I ratio, the output was the total N in milk, meat and food required to sustain the targeted number of people. The input consisted of the corrected mineral fertilizer application, deposition on the corrected area for food, feed and lucerne production, and the N fixed by legumes, field pea, fava bean, grass-clover and lucerne if they were grown on the corrected area of land. The O/I ratio was not calculated without correction because the N in surplus food and feed does not reach the people, neither in the form of food crops nor in the form of excess meat or milk. For the N surplus per hectare, any N that was available for uptake but exceeding the N demand and the N from manure, crop residues, cut and carry fertilizer, mineral fertilizer and deposition that was not available for uptake was summed. This surplus may partly be lost and partly get immobilized in the soil maintaining the soil stock. The N surplus per hectare for the corrected area of land was not determined as the N sufficiency of the rotation after correction would have to be re-calculated. Moreover, it is not realistic that different crops of a rotation are cultivated on different areas to avoid surpluses. This correction in land allocation to each crop was done only for the sake of a fair comparison of the ICLS management types.

The people and animals sustained per hectare were also calculated to compare the ICLS management types. For the calculation of the people per hectare, all lucerne grown was wholly credited to the number of people sustained per hectare. This decision was taken as any lucerne grown to meet the N requirements of feed crops which ultimately reach humans in the form of animal products. Similarly, the land used to grow feed was also credited to the people per hectare. As for the animals sustained per hectare, only the area used for feed production was considered. The herd size, milk production and the cows per hectare were used to calculate the FPCM production per hectare. The equations used in these calculations are given in Appendix C: Post-optimization calculations.

Finally, since the model was based on multiple parameters collated from literature, it follows that these may have some variation across regions and depend on many biophysical characteristics such as soil type, composition and sequence of crops in the rotation, management choices etc. For the sake of simplicity, a local sensitivity analysis varying a selected set of input parameters one-at-a-time was carried out. The chosen input parameters are shown in Table 10. The NFRVs of manure and crop residues determine the amount of N that is returned and available for use in the system. As described in Section 3.5.1, this depends on the management choices made and are therefore not fixed. This is why it was decided to assess their effect on the results of the model. Among the values of N fixation by legumes, that of clover was based on an empirical model by Høgh-Jensen et al., (2004) as presented in Thers et al., (2022), while the others were based on experimental results. Therefore, the contribution of the uncertainty of the results of the model by this parameter was also assessed. The sensitivity of the results of the model to a change in the input parameters, in either direction was represented by the percent change in uncorrected metrics, people and animals sustained per hectare, mineral N fertilizer use per hectare, N surpluses per hectare and the O/I ratio which was a metric corrected for surplus food and feed production. The formulas used was:

$$Percent\ change = \frac{Output_{\pm 10\%} - Output_{base}}{Output_{base}} * 100$$

Where $Output_{\pm 10\%}$ and $Output_{base}$ are the values of each of the metrics at ±10% and the base case, respectively.

Table 10: Changes in parameters to test the models' sensitivity

	-10%	Base	+10%	Units
NFRV of crop residues in (± 10%)	0.36	0.4	0.44	kg mineral N kg residue N^{-1}

NFRV of manure (± 10%)	0.747	0.83	0.913	kg mineral N kg manure N^{-1}
N fixation by Grass-clover (± 10%)	-15.3	-17	-18.7	kg N ha^{-1} $year^{-1}$

To understand the contribution of each parameter to the uncertainty of the results of the model, a full local sensitivity analysis would need to be conducted. Additionally, to understand the interactions between all the parameters and to visualise the entire solution surface, a global sensitivity analysis would be needed. However, keeping simplicity in mind, these were not deemed necessary for this study.

4. Results

4.1. Results of the LP model

With the input data collated and a LP model formulated per management type, as described in the materials and methods section, the following results were obtained. First, the results of each ICLS management type are presented in Section 4.1, without correction for surpluses. The corrected values are then used to compare each of the ICLS management types in Section 4.2.

4.1.1. Organic ICLS

No mineral fertilizer was allowed in the Organic ICLS. The only external input of N was through BNF by lucerne. The land allocation per rotation as a result of these constraints are presented in Table 11. The dependence on Lucerne to meet the nitrogen requirements of the system is evidenced by the land allocated to it, grown in rotation, R4. The N input to the system in R4 refers to the N added to the soil by fixation and atmospheric deposition.

Table 11: Land allocation per rotation in the Organic ICLS

	Land allocation (ha)
R1	105
R2	29
R3	70
R4	226
R5	166

The amount of each food crop produced, along with the corresponding demands of the system, in ton FM per year, are shown in Figure 1. Sugar beet has the highest amount of surplus production.

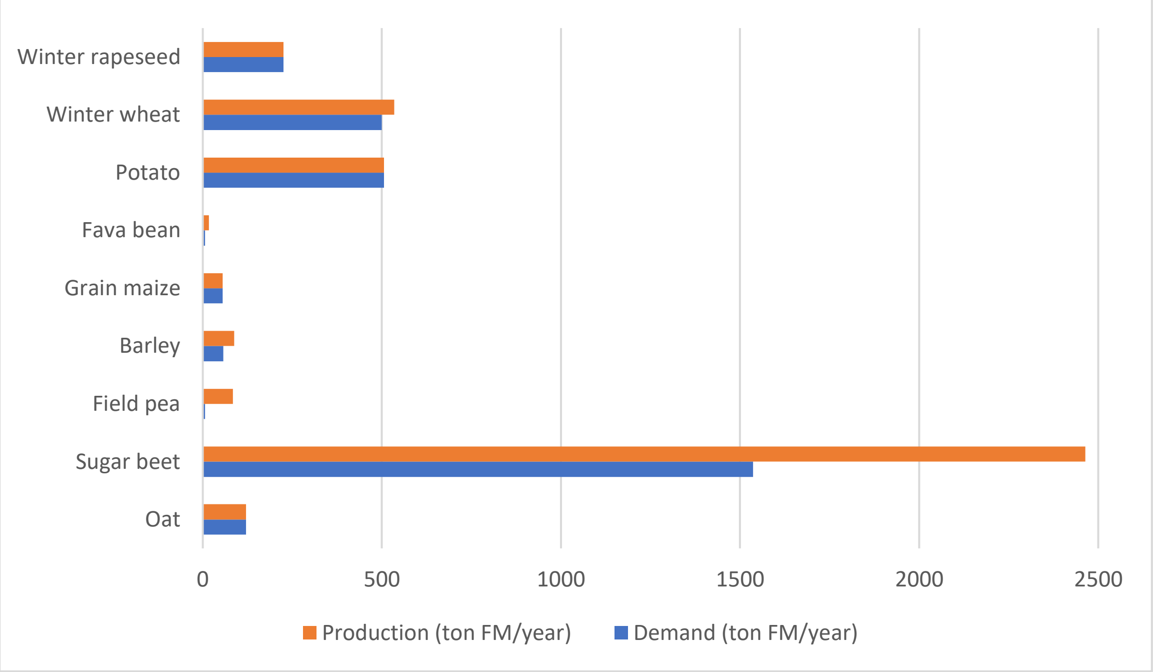

Figure 1: Food crop production and demand in the Organic ICLS in ton FM year^{-1}

The energy and protein production to feed the cattle, in terms of VEM and DVE respectively, are shown in Table 12. A surplus energy of 147 MVEM yr^{-1} and a surplus protein of 19 ton DVE yr^{-1} was produced. This is because the demands for food crops are more binding and therefore determine the land allocated per rotation. The contribution of each feed crop to the total VEM production is presented in Figure 2.

Table 12: VEM and DVE production in the Organic ICLS

	Demand	Production	Surplus
VEM (MVEM year^{-1})	458	605	147
DVE (ton DVE year^{-1})	38	57	19

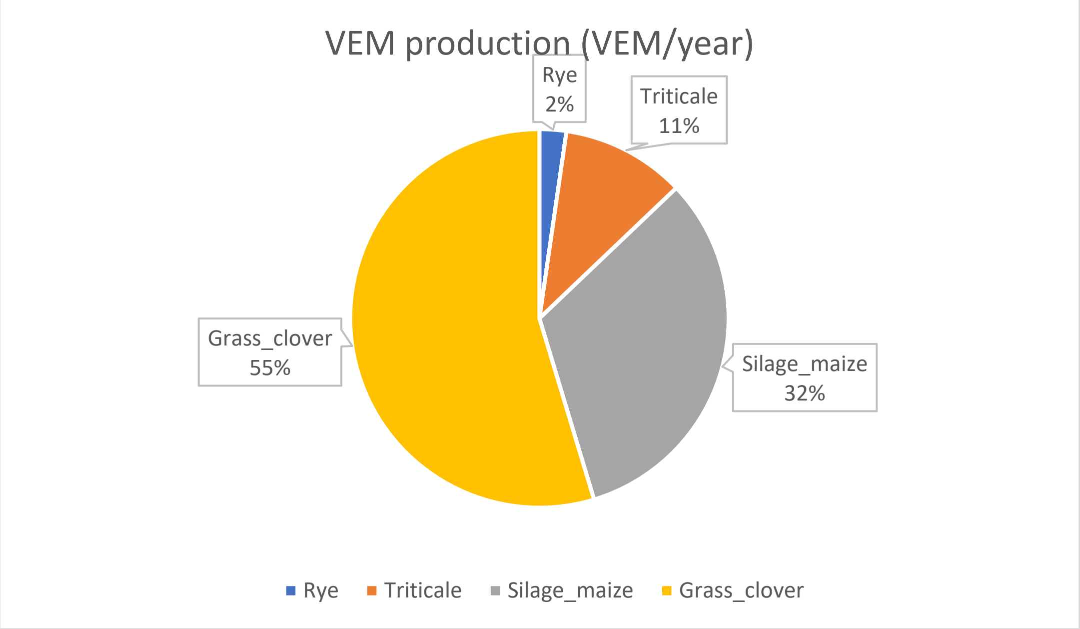

Figure 2: Contribution of feed crops to total VEM production in the Organic ICLS

In summary, the organic ICLS required 596 hectares of land, 226 ha of which was required to grow lucerne (grown in rotation R4; see Table 11). The system produced 10 ton of FPCM per hectare and could sustain approximately 12 people per hectare and 1.6 cows per hectare of feed crops. An N surplus of 131 kg N per hectare was estimated. These results are shown in Table 13. The values of metrics after correcting for surpluses are shown in Table 20. The total land required, and the number of people sustained per hectare are 7% and 9% lower after correction, respectively.

Table 13: Summary results of the Organic ICLS without correcting for surpluses

Total land requirement (ha)	596
People per hectare (pers ha^{-1})	12
Animal per hectare of feed crops (cows ha^{-1})	1.6
FPCM production per hectare of feed crops (ton FPCM ha^{-1})	10
Mineral fertilizer per ha (kg mineral N ha^{-1})	NA
N surplus (kg N ha^{-1})	131

4.1.2. Conventional ICLS

The conventional ICLS was allowed to use mineral fertilizer to meet both, food and feed N requirements. The land allocation and mineral fertilizer use in the conventional ICLS is shown in Table

14. It is expected that in order to minimize the area of land used, the system doesn't grow any lucerne to meet its nitrogen requirements since the use of mineral fertiliser was unconstrained.

Table 14: Land allocation and N sufficiency per rotation in the Conventional ICLS

	Land allocation (ha)	N fertilizer (kg N year^{-1})
R1	106	0
R2	31	2416
R3	60	6512
R4	0	0
R5	162	20763

The amount of each food crop produced, along with the corresponding demands of the system are shown in Figure 3.

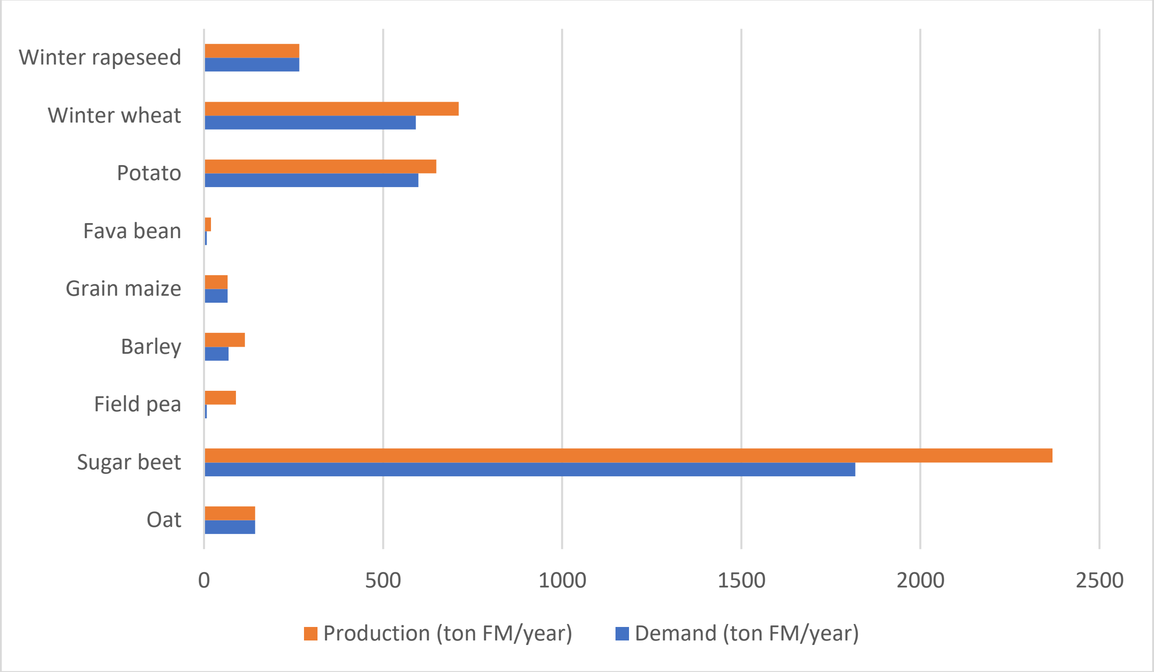

Figure 3: Food crop production and demand in the Conventional ICLS in ton FM year^{-1}

The energy and protein production to feed the cattle, in terms of VEM and DVE respectively, are shown in Table 15. While no surplus energy was produced in this ICLS, a surplus of 8 ton DVE yr^{-1} was produced. The contribution of each feed crop to the total VEM production is similar to that in the organic ICLS (see Figure 4).

Table 15: VEM and DVE production in the Conventional ICLS

	Demand	Production	Surplus
VEM (MVEM year^{-1})	610	610	0
DVE (ton DVE year^{-1})	49	57	8

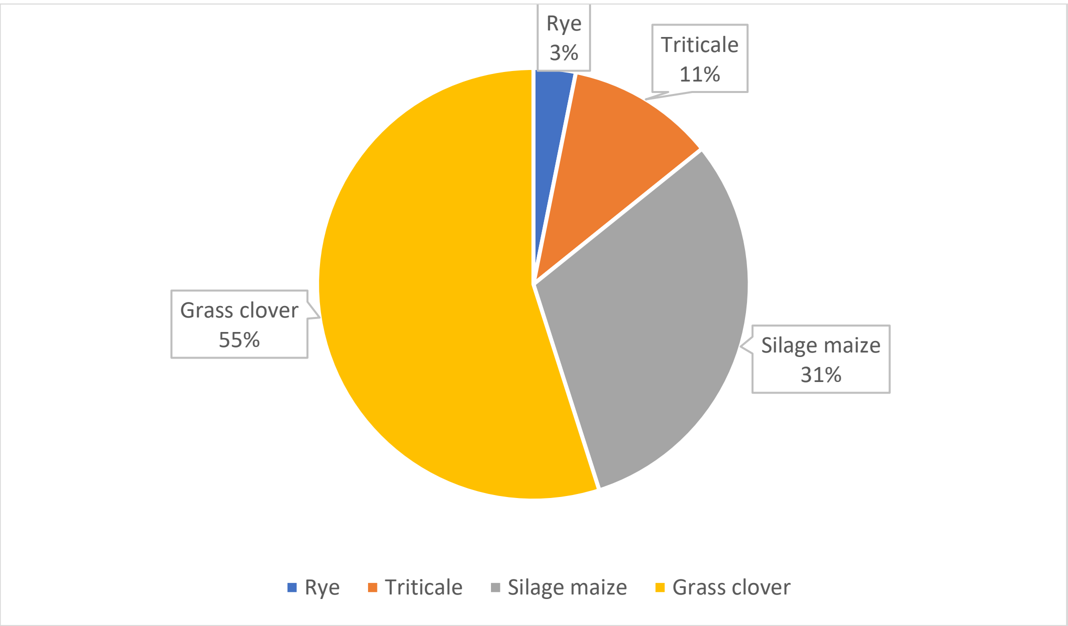

Figure 4: Contribution of feed crops to total VEM production in the Conventional ICLS

The conventional ICLS required 358 hectares in total, sustaining approximately 24 people per hectare and 1.7 cows per hectare of feed crops with a milk production of 14 ton FPCM per hectare. Here, 83 kg mineral N was used per hectare with 58 kg N per hectare left over as surplus from all inputs and return flows. The results of the optimized conventional ICLS are shown in Table 16. After correcting for surpluses (Table 20), the total land required was reduced by 6%. The milk production per hectare remained unchanged because no surplus VEM was produced.

Table 16: Summary results of the Conventional ICLS without correcting for surpluses

Total land requirement (ha)	358
People per hectare (pers ha^{-1})	24
Animal per hectare of feed crops (cows ha^{-1})	1.7
FPCM production per hectare of feed crops (ton FPCM ha^{-1})	14
Mineral fertilizer per ha (kg mineral N ha^{-1})	83
N surplus (kg N ha^{-1})	58

4.1.3. Hybrid ICLS

Mineral fertilizer was only used to meet the N requirements of food crops in the hybrid ICLS. Here too, no lucerne was grown. The land allocation and N sufficiency of the conventional ICLS is shown in Table 17.

Table 17: Land allocation and N sufficiency of rotations in the Hybrid ICLS

	Land allocation (ha)	N fertilizer (kg N year^{-1})
R1	89	0
R2	26	2041
R3	45	1220
R4	0	0
R5	136	17536

The amount of each food crop produced, along with the corresponding demands of the system are shown in Figure 5.

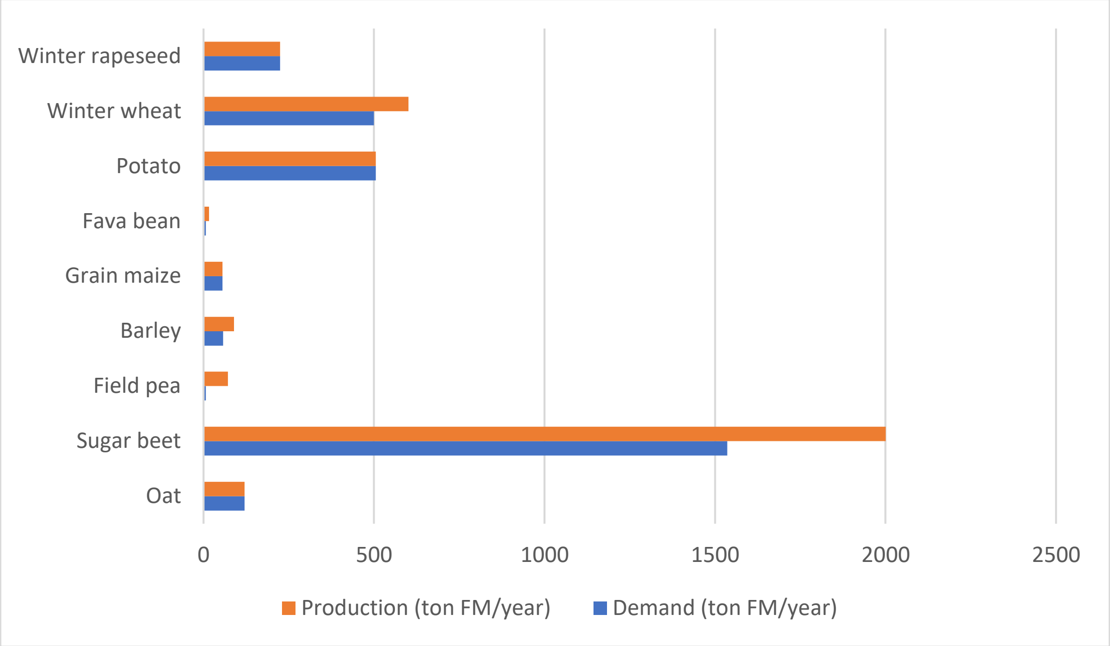

Figure 5: Food crop production and demand in the Hybrid ICLS in ton FM year^{-1}

The energy and protein production to feed the cattle, in terms of VEM and DVE respectively, are shown in Table 18. A relatively small amount of surplus VEM (5 MVEM yr^{-1}) and DVE (6 ton DVE yr^{-1}) was produced in the system. The contribution of each of the feed crops to the total VEM production are shown in Figure 6.

Table 18: VEM and DVE production in the Hybrid ICLS

	Demand	Production	Surplus
VEM (MVEM year^{-1})	458	463	5
DVE (ton DVE year^{-1})	38	44	6

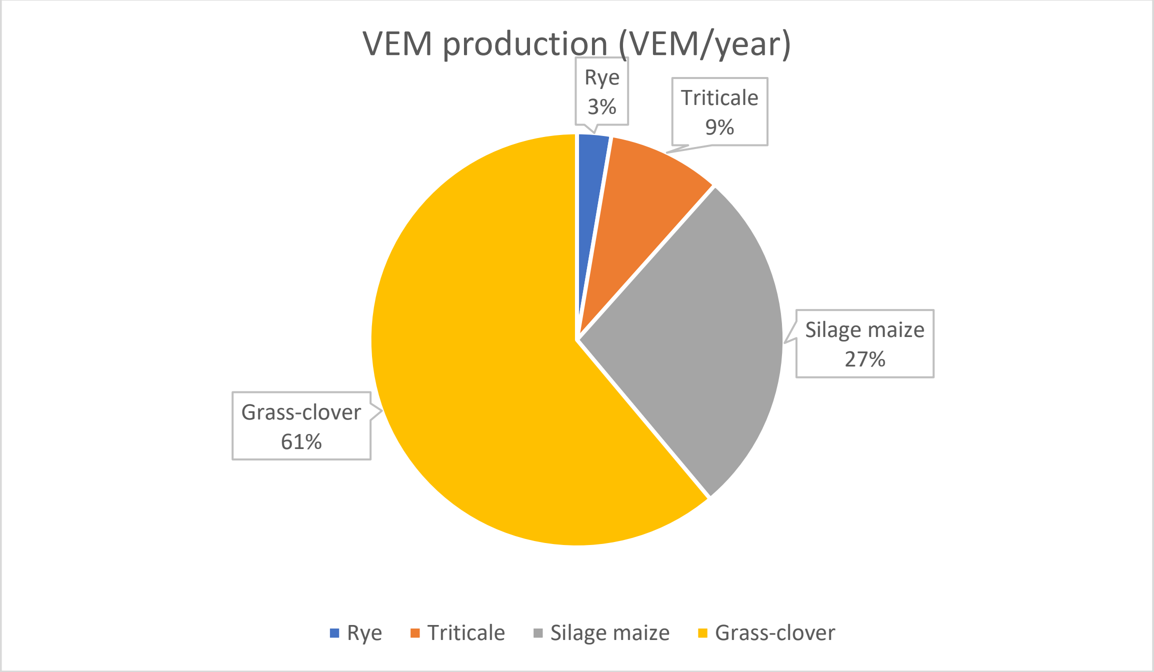

Figure 6: Contribution of each feed crop to the total VEM production in the Hybrid ICLS

The hybrid ICLS required the least amount of land among the three management types. Without correcting for surpluses, approximately 24 people and 2 cows were sustained per hectare on a total area of 297 hectares, producing 13 tons of FPCM per hectare. 70 kg mineral N was used per hectare and an N surplus of 50 kg per hectare was generated. These results are shown in Table 19. After correcting for surplus food and feed production, the total land required was reduced by 6% and there was almost no reduction in the milk production per hectare.

Table 19: Summary results of the Hybrid ICLS without correcting for surpluses

Total land requirement (ha)	297
People per hectare (pers ha^{-1})	24
Animal per hectare of feed crops (cows ha^{-1})	2.1
FPCM production per hectare of feed crops (ton FPCM ha^{-1})	13
Mineral fertilizer per ha (kg mineral N ha^{-1})	70
N surplus (kg N ha^{-1})	50

4.2. Comparison of ICLS management types

A decision was taken to correct the land for the surplus food and feed production so that the management types could be compared. However, the corrected land was reduced by at most 7% and almost uniformly across all management types. This shows that the total land requirements are comparable without correction. Nonetheless, comparing corrected results ensures a fair comparison between the number of people and animals per hectare, across management types. The corrected values are presented in Table 20. We see that the people sustained per hectare was the same in the conventional ICLS and the hybrid ICLS and about twice that of the organic ICLS. Although, the animals sustained per hectare was the same in all three systems, the hybrid ICLS sustained the highest number of animals. The conventional ICLS had the highest milk productivity and the hybrid ICLS was approximately an average of the organic and the conventional ICLS. Further, the hybrid ICLS used 16%

less mineral fertilizer than the conventional ICLS (46 and 55 kg N ha^{-1} respectively) and at a 14% higher O/I ratio (0.72 and 0.63 respectively).

Table 20: Indicators of each management type after correcting for surplus food and feed production

	Organic ICLS	Conventional ICLS	Hybrid ICLS
Total land requirement (ha)	559	337	280
People per hectare (pers ha^{-1})	13	26	26
Animal per hectare of feed crops (cows ha^{-1})	1.8	1.7	2.1
FPCM production per hectare of feed crops (ton FPCM ha^{-1})	11	14	13
Mineral fertilizer per ha (kg mineral N ha^{-1})	NA	55	46
O/I ratio (-)	0.28	0.63	0.72

4.3. Sensitivity analysis

Three of the input parameters, the NFRVs of residues, manure and the N fixed by grass-clover and transferred to the soil were varied by ±10% to see the variation in the results. The percent changes in the results in response to this change in the input parameters are presented in Table 21, Table 22 and Table 23, respectively. All metrics presented, except the O/I ratio, are without correction for surplus food and feed production. As described in Section 3.7, the O/I ratio was calculated only after correcting for surplus food and feed production. We see that the response to the variations in the metrics are largely symmetric between the positive and negative directions of the input parameter variations suggesting a continuous linear relationship between the input parameter and the output variables, over the considered range. This would have to be verified by considering intermediate variations within the range, but it was not considered necessary for this study.

Among the three management types, the organic ICLS is the most sensitive to changes in the NFRV of crop residues (see Table 21). This is because the system's main source of nitrogen input is the lucerne used as cut & carry fertilizer and it is the only system that needs to grow lucerne to meet its N demands. This directly influences the land requirement and explains the variation in the people sustained per hectare. It doesn't change the animals sustained or the milk production per hectare because the area required to grow lucerne was wholly credited to the people sustained per hectare. The other management types show smaller variations in the N fertilizer used, the O/I ratio and the N surplus per hectare.

Table 21: Percent changes of metrics in response to a 10% variation in NFRV of residues

	Organic ICLS			Conventional ICLS			Hybrid ICLS		
	-10%	Base	+10%	-10%	Base	+10%	-10%	Base	+10%
People per hectare (pers ha^{-1})	-5	12	5	0	24	0	0	25	0
Animal per hectare (cows ha^{-1})	0	1.6	0	0	1.7	0	0	2.1	0
FPCM production per hectare (ton FPCM ha^{-1})	0	10	0	0	14	0	0	13	0
Mineral fertilizer per ha (kg mineral N ha^{-1})	NA	NA	NA	2	83	-2	2	70	-2
N surplus (kg N ha^{-1})	9	131	-8	1	58	-1	1	50	-1
O/I ratio (-, corrected)	-10	0.28	10	-1	0.63	1	-1	0.72	1

Changes in the NFRV of manure affect the results negligibly for all management types (see Table 22). Changes in the NFRV of manure only affects the N surpluses per hectare and the mineral fertilizer use per hectare, in all management types except for the organic ICLS. Here, an increase or decrease in the NFRV of manure decreases or increases the land required to grow lucerne, respectively, to meet the system's N requirements. This explains the variation in the people sustained per hectare. In both, the conventional and the hybrid ICLS an increase in the NFRV does not improve the O/I ratio because the N returned in manure is an internal flow and is not considered an input. In the conventional ICLS, a decrease in NFRV of manure increases the need for mineral fertilizer and thus affects the O/I ratio whereas in the hybrid ICLS, the change of NFRV of manure just results in a change in the allocation of manure between food and feed crops without changing the mineral fertilizer input.

Table 22: Percent changes of metrics in response to a 10% variation in NFRV of manure

	Organic ICLS			Conventional ICLS			Hybrid ICLS		
	-10%	Base	+10%	-10%	Base	+10%	-10%	Base	+10%
People per hectare (pers ha^{-1})	-1	12	1	0	24	0	0	25	0
Animal per hectare (cows ha^{-1})	0	1.6	0	0	1.7	0	0	2.1	0
FPCM production per hectare (ton FPCM ha^{-1})	0	10	0	0	14	0	0	13	0
Mineral fertilizer per ha (kg mineral N ha^{-1})	NA	NA	NA	4	83	0	0	70	0
N surplus (kg N ha^{-1})	2	131	-2	3	58	3	-2	50	2
O/I ratio (-, corrected)	-3	0.28	3	-2	0.63	0	0	0.72	0

The response of the models to a change in the amount of N fixed by clover is negligible (see Table 23). In the organic ICLS, only the O/I ratio changes and this is because of a change in N input from fixation by clover. In the conventional ICLS, a change in the amount of N fixed, in either direction, leads to an increase in mineral fertilizer and N surplus by 1 percent. In both cases, a larger proportion of the crop residues are allocated to meet the N demands of the feed crops leading to an increase in mineral fertilizer use to meet N requirements of food crops. This leads to an increase in the N surplus in both cases. The O/I ratio increases when N fixation is reduced because the input is reduced and vice versa when the N fixation increases. The decrease in O/I ratio is slightly higher in response to an increase in N fixation because not only does the N input from fixation increase but also the mineral fertilizer use is higher. This behaviour is not significant in the hybrid ICLS leading to a symmetric, inversely proportional change only in the O/I ratio.

Table 23: Percent changes of metrics in response to a 10% variation in N fixation by clover

	Organic ICLS			Conventional ICLS			Hybrid ICLS		
	-10%	Base	+10%	-10%	Base	+10%	-10%	Base	+10%
People per hectare (pers ha^{-1})	0	12	0	0	24	0	0	25	0
Animal per hectare (cows ha^{-1})	0	1.6	0	0	1.7	0	0	2.1	0
FPCM production per hectare (ton FPCM ha^{-1})	0	10	0	0	14	0	0	13	0
Mineral fertilizer per ha (kg mineral N ha^{-1})	NA	NA	NA	1	83	1	0	70	0
N surplus (kg N ha^{-1})	0	131	0	1	58	1	0	50	0
O/I ratio (-, corrected)	1	0.28	-1	1	0.63	-2	2	0.72	-2

Thus, except in the case of a change in the NFRV of manure, for the organic ILCS, the changes in the results of the model are not significant in response to a 10% variation in the NFRVs of manure and crop residues and the N fixation by clover. To better understand the uncertainty of the results of the model, a full local sensitivity analysis could be conducted.

5. Discussion

5.1. Discussion of main outcomes

This thesis sought to assess the yield and environmental performance of a combination of organic feed and conventional food production in an ICLS using a linear optimisation approach. We see from Table 20, that the hybrid ICLS sustained a comparable number of people per hectare to that of the conventional ICLS (25 and 24 people ha^{-1}, respectively) and 108% more than the organic ICLS (12 people ha^{-1}). After correcting for surpluses, the hybrid ICLS had an O/I ratio that was 14% higher (0.72) than that of the conventional ICLS (0.63) and 157% higher than that of the organic ICLS (0.28).

Approximately 38% of the land in the organic ICLS was used to grow lucerne (226 ha; see Table 11). Excluding the land used to grow lucerne in the organic ICLS, the people sustained per hectare for the same number of people in the hybrid ICLS was 25% higher (20 people ha^{-1}). This is in line with the currently accepted relative yield gap of 19-25% between organic and conventional management as reported by Seufert, (2019). Of course, this is to be expected as the relative yield gaps per crop between organic and conventional management taken from de Ponti et al. (2012), were also an average of 26%. Further, there are no differences in the milk and meat productivities of the cows in the organic and the hybrid ICLS. Therefore, this difference of the number of people that can be sustained can be attributed entirely to the differences in food crop yields in the two ICLS management types. However, in practice these relative yield gaps may vary based on factors like climatic conditions and management practices of each farm.

The number of animals sustained per hectare of feed crop was highest in the hybrid ICLS with 2.1 animals per hectare, followed by 1.7 and 1.6 animals per hectare in the conventional and the organic ICLS (see Table 20). It is interesting to note that although both, the hybrid and the organic ICLSs have organically managed dairy components, the land requirement per animal was different. This is because the yield gap of the food crops between the management types lead to different land allocations per rotation. Thus, the share of feed crops produced to meet the required VEM production was different (compare Figure 4 and Figure 6). Even after deducting the surplus production, there was still a difference in land requirements because the organic ICLS produced a larger share of silage maize than the hybrid ICLS (32% and 27% respectively) and silage maize was less productive under organic management leading to a higher land requirement.

The milk production per hectare in the conventional and the hybrid ICLS was comparable (see Table 20). This was 30% lower for the organic ICLS (10 ton FPCM ha^{-1}) than in the hybrid ICLS (13 ton FPCM ha^{-1}). Two factors explain this: the first is that milk productivity of cows under organic management is lower and secondly, in all the ICLS management types, it is the food crops that are binding and thus determine the land allocated to the rotation i.e., the area used to grow the required feed is a consequence of the demand of the food crops. The latter reason is evidenced by the production of one food crop per rotation exactly equal to the demand in Figure 1, Figure 3 and Figure 5 and that all management types except the conventional ICLS produced surplus VEM and DVE. In the case of the conventional ICLS, the marginal value (data not shown) of the VEM production was close to 0 indicating that a relaxation in the constraint would not change the land allocation considerably.

In Germany, the available arable land per person is 0.14 hectare per person or 7 people per hectare (FAO, n.d.). This includes "… land under temporary crops (double-cropped areas are counted once), temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned as a result of shifting cultivation is excluded." Although the results of this analysis showed land requirements well within this range, for all management types, it is important to note that this analysis did not consider the land requirement to meet a full human diet and only considered milk, beef, and veal production from the livestock component and a limited number of food crops.

In summary, it can be concluded that a hybrid ICLS is potentially more N efficient than both, a conventional ICLS and an organic ICLS, as defined in this study and does not compromise on the system's yield performance. Therefore, it could be a promising means to the sustainable intensification of agriculture.

5.2. Methodological choices and assumptions

As described in Section 3.7, the N sufficiency constraints were separated for food and feed crops which means that the N fixed by food and feed legumes could not be exchanged between these crop groups. An LP formulation that remedies this is expected to further reduce the land requirements, the external N inputs and/or the O/I ratios of the management types. However, since all the management types had the same treatment, the comparison of the systems is still valid.

In this analysis, the NFRVs of manure and crop residues were taken from a synthesis of a number of long term experiments (Hijbeek et al., 2018). However, in reality, these values are not absolutes and are influenced by various factors such as local climatic conditions, soil conditions, management choices and the choice and sequence of crops in the rotation.

To calculate the N output of the system, the N content of milk, meat and the crop products were estimated from their protein contents. In the conversion of the protein content to the N content, Kjeldahl factors of 6.25 for food crops and meat was used and a factor of 6.38 was used for milk (Maubois & Lorient, 2016). It was seen that the use of more specific conversion factors for different crops, known as Jones factors have also been proposed (FAO, 2002). This is because the factor of 6.25 is based on an average protein N content of 16% but in reality, this varies per crop. However, this level of specification was not considered necessary for this analysis and the resultant differences in the results were not expected to be significant.

The VEM content of dehydrated grass was used as for the VEM content of grass-clover. This is not expected to make a significant difference as the ECM production per kg of dry matter intake for red-clover, perennial ryegrass and a combination of the two are comparable (Johansen et al., 2017). Further, this analysis assumed the same yield of grass-clover under both, organic and conventional management. This has a considerable influence on the N inputs to the system in from clover BNF.

In this analysis, the feed crop production did not bind the land allocation in any rotation. However, when a larger herd or a more diverse herd is considered, part of the crop residues may be used to feed the animals and the remainder may be returned to the soil either by direct incorporation or in combination with manure to reduce ammonia volatilization.

5.3. Comparison with other research

To my knowledge, such hybrid management of ICLSs has not been studied extensively. However, a study in Brazil compared the NUE and N balance of ICLSs consisting of a monocrop cultivation of grain maize and the production of beef cattle in pasture, with and without the use of herbicide. Their ICLSs had maize and pastures of palisade grass, intercropped. Their N inputs included urea equivalent to urea fertilizer with 45% N and organic residues consisting of crop residues, manure and urine. While these N flows along with N volatilization were monetarily valued, the N balance considered only N input as mineral fertilizer and N export in maize grains and animal tissue. This explains their high NUE values, defined as the ratio of N output to N input, of 89-99% (Oliveira et al., 2022).

Farias et al. (n.d.) took a similar approach as in this analysis to ICLSs where a “system fertilisation” approach was compared with a conventional fertilisation strategy. The “system fertilization” is a conceptual framework (Assmann et al., 2017) considering the spatial and temporal dynamics of nutrients. It involves the application of fertilizer in a system phase that represents low nutrient extraction and high nutrient cycling capacity to maximise total system production. They found that the system fertilization approach led to higher herbage production and higher combined energy production from sheep meat and soybean yields. In relation to this analysis, their study can be considered a hybrid management where feed crops are managed conventionally, and food crops were managed organically. Some of the key differences are that 1) the effect of phosphorous and potassium fertilisation strategies was studied with a constant application of nitrogen during the pasture establishment phase across treatments unlike in this study where only nitrogen fertilisation was considered; even so, the only food crop considered was soybean which is a legume and derives most of its nitrogen from BNF and 2) energy production from the livestock component consisted only of sheep meat and not milk. In any case, such a system fertilization approach could be an alternative fertilization strategy in contrast to a segmented approach of using synthetic fertilizer either on food or on feed crops, as considered in this study.

5.4. Outlook and opportunities for future research

The price premiums received on products of organic agriculture are seen to be an important way to compensate for its lower yields. However, a combination of organic and conventional management may be prohibitive from a certification perspective in this regard. Even so, it has been suggested that the breakeven premiums needed to match profits from conventional agriculture ranges from 5-7% for yields that are 10-18% lower (Crowder & Reganold, 2015). When a dairy component is combined, this margin may increase slightly. However, this margin does not include any payments for ecosystem services from organic agriculture. Therefore, if regulations cannot be adapted to accommodate such a hybrid management, the financial gap to be closed is not expected to be very significant.

ICLSs in general, are seen to improve the resilience of agricultural systems by distributing risks over a diversity of products, improve resource use efficiencies and deliver ecosystem services that are not typically provided by specialised systems. This study illustrates that the hybrid ICLS represents an optimal combination of organic and conventional management strategies, resulting in yield performance comparable to a conventional ICLS and a better N O/I ratio than both the organic and conventional ICLS. In this sense, the hybrid ICLS can be considered a 'golden mean' between the two approaches, that reduces the externalities of excessive reliance on synthetic inputs without sacrificing yield performance. While this analysis considered the same crop rotations and manure application across ICLS management types, this is not always the case. For example, Farias et al., (2020) and Oliveira et al., (2022), both used crop rotations of only two crops. Additionally, although Farias et al., (2020) compared phosphorous and potassium fertilisation strategies they did not consider the use of manure in both, their conventional and system fertilization strategies. Therefore, in such cases the hybrid management of ICLSs may present additional improvements over conventional and organic ICLSs where manure management and crop rotations are not adapted. The design of an optimal crop rotation, however, is not trivial, especially for such a hybrid system. Bosland (2022), used a linear optimisation approach to generate optimum crop rotations for the north of the Netherlands, considering alternative scenarios of diets and human populations along with land suitability classes for a set of crops. Similarly, the optimisation of crop rotations specific to such a hybrid system might present an interesting research opportunity. Adaptation of specific management practices to a hybrid system may include practices such as mixing manure with straw to increase its C/N ratio and reduce N losses via ammonia volatilization. This along with an optimized crop rotation that takes advantage of varying N demands over time and space may further accentuate the benefits of such a hybrid system.

Hybrid management of integrated crop-livestock systems (ICLSs) can also enhance the provision of ecosystem services, including pest control and preserving biodiversity. Although organic systems are seen to have lower pest populations than conventional systems, it is an important yield reducing factor for organic systems. However, landscape heterogeneity is seen to greatly augment the systems' capacity to control pests (Garrett et al., 2017; Östman et al., 2001). A similar influence of organic management in combination with landscape heterogeneity on farmland biodiversity has been reported (Rundlöf et al., 2008; Seufert & Ramankutty, 2017). Therefore, hybrid management in an ICLS could facilitate an increase in farmland biodiversity and landscape diversity with improved pest control due to a wider variety of natural enemies and the assistance of conventional crop protection inputs. However, this needs to be further researched as the use of conventional crop protection inputs could also dampen the effect of increased biodiversity due to landscape diversity and organic management. Based on this, it is expected that such a hybrid ICLS could benefit from being part of a system with a diverse set of land-use types.

In fact, such a modelling approach could be extended to simulate collaboration between a wider variety of land-use types, potentially leading to better nutrient use efficiencies. Further nuances to operationalizing such collaborations *e.g.*, logistical aspects of storing and transporting feed and manure and financial aspects of such collaborations may also be taken into account. Jongeneel et al. (2021) suggest that an average net income reduction of 32% and a herd reduction of 9% is expected in dairy cases as a result of the EU's Farm to Fork (F2F) and Biodiversity strategies. The results of this study show that the hybrid management of ICLSs shows potential for N efficiency improvement over organic and conventional ICLs, without suffering yield losses. Therefore, such production systems could contribute to the F2F's goal of reducing fertilizer use and nutrient losses. The other ecosystem service attributed to OA is the improvement of soil health, indicated by soil organic carbon content. Although leys are expected to sequester less carbon than permanent grasslands, such hybrid management could provide an opportunity for both, the long-term maintenance or improvement of soil organic carbon content while meeting more short-term nutrient requirements through synthetic inputs that are administered judiciously. The implementation of such collaborations and combinations of organic and conventional management could also be conducted to get more empirical data on yield and nutrient cycling performance. This could help better capture synergies and trade-offs to the hybrid management of the integration of multiple land-use types, that such a model based purely on average data cannot fully capture.

6. Conclusions

The results of this analysis show that the performance of the hybrid ICLS represents a golden mean between the extremities of a conventional and an organic ICLS. In conclusion, it can be said that the hybrid management of ICLSs show potential synergistic effects and has potential as a means to the sustainable intensification of agriculture. Data from the implementation of such hybrid management can help capture synergies and trade-offs between the combination of the two management types that such a model based on average data may not be able to fully capture. More complex collaboration between a diverse set land-use types can also be explored in pursuit of valorising more side streams and improving resource use efficiencies.

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Appendix A

List of parameters and their units

Parameter	Organic	Conventional	Unit
Annual consumption beef-carcass	16		kg beef carcass person^{-1} year^{-1}
Annual consumption veal-carcass	1		kg veal carcass person^{-1} year^{-1}
Culling age calves	0.67		year
Daily consumption milk	0.75		kg std milk person^{-1} day^{-1}
Demand beef	11		kg beef person^{-1} year^{-1}
Demand FPCM	72		kg FPCM person^{-1} year^{-1}
Demand veal	1		kg veal person^{-1} year^{-1}
Dressing fraction calves	0.54		kg veal carcass kg LW^{-1}
Dressing fraction cows	0.58		kg beef carcass kg LW^{-1}
DVE lactation	33943	44141	kg DVE year^{-1}
DVE maintenance	3753	4720	kg DVE year^{-1}
DVE total	37696	48862	kg DVE year^{-1}
Energy content beef	8		MJ kg beef^{-1}
Energy content FPCM	3		MJ kg FPCM^{-1}
Energy content veal	9		MJ kg veal^{-1}
Energy demand dairy animal products	318		MJ person^{-1} year^{-1}
Energy supply beef	23930	37842	MJ year^{-1}
Energy supply dairy animal products	2171031	2764265	MJ year^{-1}
Energy supply veal	34532		MJ year^{-1}
Fraction beef	0.42		kg beef kg LW^{-1}
Fraction calves retained for fattening	0.25		-/-
Fraction veal	0.42		kg veal kg LW^{-1}
Human energy consumption daily	10		MJ day^{-1}
Human Energy demand arable[8]	21914041	25913791	MJ year^{-1}
Human protein consumption daily	81		g day^{-1}
Human protein demand arable	89225	105511	kg protein year^{-1}
Lifespan dairy cow	6		year
LW calf	349		kg LW calf^{-1}
LW cow	430	680	kg LW cow^{-1}
FPCM energy supply	2112569	2691891	MJ year^{-1}
FPCM protein supply	22489	28656	kg protein year^{-1}
FPCM productivity	6429	8192	kg FPCM cow^{-1} year^{-1}
N requirement	N requirements and fixation per crop in Table 9		kg N ha^{-1} yr^{-1}
No. of cows	106		# cows
No. people sustained based on energy requirements from dairy products	7351	8704	# people
No. people sustained based on protein requirements from dairy products	4919	6266	# people

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[8] Based on number of people whose energy requirements can be met

Production beef	3191	5046	kg beef year^{-1}
Production veal	3884		kg veal year^{-1}
Protein content beef	0.200		kg protein kg beef^{-1}
Protein content FPCM	0.033		kg protein kg FPCM $^{-1}$
Protein content veal	0.190		kg protein kg veal^{-1}
Protein demand dairy animal products	5		kg protein person^{-1} year^{-1}
Protein supply beef	638	1009	kg protein year^{-1}
Protein supply dairy animal products	23865	30403	kg protein year^{-1}
Protein supply veal	738		kg protein year^{-1}
Replacement fraction	0.25		-/-
Standard fat content in milk	0.044		kg fat kg milk^{-1}
Standard protein content in milk	0.034		kg protein kg milk^{-1}
Total FPCM production	681474	868352	kg FPCM year^{-1}
Urea milk	20.2		g N kg FPCM^{-1}
VEM demand	458083734	609655817	VEM year^{-1}

Appendix B

Yield and yield component data for crops

Data used to calculate the input parameters and their sources are presented here. Table 24 shows the relative yield gap of organic management compared to conventional management for each crop. The yield gaps were taken from (de Ponti et al., 2012). No yield gap was considered for grass-clover.

Table 24: Relative yield gap between organic and conventional management

Crops	Relative yield gap (de Ponti et al., 2012)
Winter wheat	0.73
Barley	0.69
Oat	0.85
Grain maize	0.89
Fava bean	0.91
Field pea	0.88
Potato	0.70
Sugar beet	1.05
Winter rapeseed	0.82
Rye	0.76
Triticale	0.81
Silage maize	0.89
Grass clover	-
Lucerne	0.9

Table 25 shows the sources for the conventional yields and the DM fractions presented in Table 8.

Table 25: Sources of data presented in Table 8

Crops	Conventional yields (ton FM ha^{-1})	DM fraction (ton DM/ton FM)
Winter wheat	(Global Yield Gap Atlas, n.d.)	(Global Yield Gap Atlas, n.d.)
Barley	(Global Yield Gap Atlas, n.d.)	(Global Yield Gap Atlas, n.d.)
Oat	(FAO, 2023)	(Grains Research and Development Corporation, 2016)
Grain maize	(Global Yield Gap Atlas, n.d.)	(Global Yield Gap Atlas, n.d.)
Fava bean	(Skovbjerg et al., 2020)	(Skovbjerg et al., 2020)
Field pea	(Karkanis et al., 2016)	(Karkanis et al., 2016)
Potato	(FAO, 2023)	(Goffart et al., 2022)
Sugar beet	(DBV, 2020)	(Bosland, 2022)
Winter rapeseed	(FAO, 2023)	(Grains Research and Development Organisation, 2023)
Rye	(FAO, 2023)	(Grains Research and Development Corporation, 2018a)
Triticale	(FAO, 2023)	(Grains Research and Development Corporation, 2018b)
Silage maize	(Heuze et al., 2017)	(Heuze et al., 2017)
Grass clover	(Nevens & Reheul, 2002; Thers et al., 2022)	(Nevens & Reheul, 2002; Thers et al., 2022)
Lucerne	(Agriculture and Horticulture Development Board, 2023a)	(Agriculture and Horticulture Development Board, 2023a)

The data used to calculate the N in residues of the various crops are presented in the following tables along with their sources. Since the whole crop is used for ensiling maize, N in residues was not calculated. A value of 169 kg N was estimated to be fixed by grass-clover from Thers et al., (2022) and an N concentration of 3% was used for Lucerne from Van Der Burgt & Rietema, (2018). The N in fava bean crop residues was obtained directly from (Neugschwandtner et al., 2015). A crop residue nitrogen content of 0.73% on a dry matter basis was obtained for grain maize from (Ludemann et al., 2022). The N content in residues of sugar beets was calculated from data in (Laufer et al., 2016). A protein content of 13% in oats was used to calculate the N in residues based on its NHI (Rasane et al., 2015). The HIs, NHIs and the N concentrations in crop residues used to estimate the N in residues for the rest of the crops are presented below.

Table 26: Harvest indices of crops

Crops	HI	Sources
Winter wheat	0.51	(Agriculture and Horticulture Development Board, 2023b)
Barley	-	-
Oat	0.34	(Kaul et al., 2000)
Grain maize	-	-
Field pea	0.47	(Lecoeur & Sinclair, 2001)
Potato	0.82	(Zebarth et al., 2004)
Sugar beet	0.78	(Laufer et al., 2016)
Winter rapeseed	0.23	(Luo et al., 2015)
Rye	-	-
Triticale	-	-

Table 27: NHIs of crops

Crops	NHI	Sources
Winter wheat	0.68	(Agriculture and Horticulture Development Board, 2023b)
Barley	0.73	(Agriculture and Horticulture Development Board, 2022)
Oat	0.70	(Rattunde & Frey, 1986)
Grain maize	-	-
Potato	0.71	(Zebarth et al., 2004)
Sugar beet	0.49	(Laufer et al., 2016)
Winter rapeseed	0.58	(Stepaniuk & Głowacka, 2021)
Rye	0.78	(Brancheorganisatie Akkerbouw, 1999)
Triticale	0.80	(Sobkowicz & Śniady, 2004)

Table 28: N concentrations of crop residues

Crops	N concentration in residues (kg N kg DM^{-1}; Nijhof, 1987)
Field pea	0.0195
Winter rapeseed	0.0105

Appendix C

Objective function and constraints to the LP model

Set definitions

Set	Description	Elements
rot	Crop rotations	R1, R2, R3, R4
food_crop	Food crops	Winter_wheat, Barley, Oat, Grain_maize, Fava_bean, Field_pea, Potato, Sugar_beet, Winter_rapeseed
feed_crop	Feed crops	Rye, Triticale, Silage_maize, Grass_clover
Legume	Legume grown as Cut & Carry fertilizer	Lucerne

Variables

Parameter	Description	Unit
var_X_{rot}	Amount of land allocated to each rotation	ha
var_X_total	Total amount of land used across all rotations	ha
var_N_manure_feed	Amount of manure used to fertilise feed crops in hybrid management	kg N ha^{-1} yr^{-1}
var_N_manure_food	Amount of manure used to fertilise food crops in hybrid management	kg N ha^{-1} yr^{-1}
var_N_fert_food	Amount of N supplied to food crops through mineral fertilisers	kg N yr^{-1}
var_N_fert_feed	Amount of N supplied to feed crops through mineral fertilisers	kg N yr^{-1}
$var\_DVE\_production_{feed\_crop,rot}$	Total protein produced for animals, per feed crop per rotation	ton DVE yr^{-1}
$var\_VEM\_production_{feed\_crop,rot}$	Total energy produced for animals, per feed crop per rotation	VEM yr^{-1}
var_N_input_legume	N input to R4 through fixation by lucerne and deposition	kg N yr^{-1}
$var\_N\_demand\_food_{rot}$	Food crop N requirements per rotation	kg N yr^{-1}
$var\_N\_demand\_feed_{rot}$	Feed crop N requirements per rotation	kg N yr^{-1}
var_N_demand_legume	N fixation into the soil by Lucerne	kg N yr^{-1}
$var\_N\_supply\_residue\_feed_{rot}$	N inputs from crop residues to feed crops per rotation	kg N yr^{-1}

var_N_supply_residue$_{\text{rot}}$	N available in food and feed crop residues per rotation	kg N yr^{-1}
var_N_supply_legume	N available from lucerne residues	kg N yr^{-1}
var_N_supply_manure_food$_{\text{rot}}$	N available to food crops from manure	kg N yr^{-1}
var_N_supply_manure_feed$_{\text{rot}}$	N available to feed crops from manure	kg N yr^{-1}
var_legume_food$_{\text{rot}}$	N requirements of food crops per rotation met through Lucerne residues used as Cut&Carry fertilizer	kg N yr^{-1}
var_legume_feed$_{\text{rot}}$	N requirements of feed crops per rotation met through Lucerne residues used as Cut&Carry fertilizer	kg N yr^{-1}
var_deposition_food$_{\text{rot}}$	N deposition from growing food crops per rotation	kg N yr^{-1}
var_deposition_feed$_{\text{rot}}$	N deposition from growing feed crops per rotation	kg N yr^{-1}
var_deposition_legume	N deposition on area used to grow lucerne	kg N yr^{-1}

Parameter definitions and units

Parameter	Description	Unit
num_people	Number of people to be sustained based on the production of milk and meat from the dairy farm	# people
hum_dem$_{\text{food\_crop}}$	Human demands for food crops	ton FM pers^{-1} year^{-1}
Y$_{\text{food\_crop}}$	Yield per food crop	ton FM ha^{-1} year^{-1}
Y$_{\text{feed\_crop}}$	Yields per feed crop	ton FM ha^{-1} year^{-1}
DM_frac$_{\text{feed\_crop}}$	Dry matter fraction per feed crop	ton DM ton FM^{-1}
crop_freq$_{\text{food\_crop, rot}}$	Cropping frequency per food crop per rotation	(-)
crop_freq$_{\text{feed\_crop, rot}}$	Cropping frequency of feed crop per rotation	(-)
DM_frac$_{\text{feed\_crop}}$	Dry matter fraction per feed crop	ton DM ton FM^{-1}
VEM_dem	VEM requirement of the full herd	VEM year^{-1}
DVE_dem	DVE requirement of the full herd	ton DVE year^{-1}
VEM$_{\text{feed\_crop}}$	VEM content per feed crop	VEM ton DM^{-1}
DVE$_{\text{feed\_crop}}$	DVE content per feed crop	ton DVE ton DM^{-1}
N_req$_{\text{food\_crop}}$	N requirement per food crop	kg N ha^{-1} yr^{-1}
N_req$_{\text{feed\_crop}}$	N requirements per feed crop	kg N ha^{-1} yr^{-1}
N_legume	N fixed by Lucerne	kg N ha^{-1} yr^{-1}

N_Manure	N available in the manure	kg N yr^{-1}
uptake_eff	Annualised long-term recovery of mineral fertilisers	kg N taken up kg supplied^{-1}
NFRV_manure	N fertiliser replacement value of manure	kg mineral N kg manure N^{-1}
N_residue$_{rot}$	Amount of N in crop residues per rotation	kg N ha^{-1}
NFRV_residue	N fertiliser replacement value of crop residues	kg mineral N kg residue N^{-1}
N_manure_loss	N losses associated with livestock housing, grazing, and manure storage	kg N lost kg N excreted^{-1}
deposition	Average N deposited annually in Germany	kg N ha^{-1} yr^{-1}

LP formulation

Objective:

$$\min(var\_X\_total) = \sum_{rot} var\_X_{rot}$$

Subject to constraints,

$e\_human\_nutrition_{food\_crop}$..

$$\sum_{rot} Y_{food\_crop} * crop\_freq_{food\_crop,rot} * var\_X_{rot} \geq \mathrm{hum\_dem}_{food_{crop}} * num\_people$$

$$\forall food\_crop$$

e_VEM..

$$\sum_{feed\_crop,rot} var\_VEM\_production_{feed\_crop,rot} \geq VEM\_dem$$

e_DVE..

$$\sum_{feed\_crop,rot} var\_DVE\_production_{feed\_crop,rot} \geq DVE\_dem$$

def_N_legume_partition..

$$\sum_{rot} var\_legume\_food_{rot} + var\_legume\_feed_{rot} = var\_N\_supply\_legume$$

e_manure..

$$\sum_{rot|rot\neq"R4"} (var\_N\_manure\_food_{rot} + var\_N\_manure\_feed_{rot}) = N\_manure$$

e_N_sufficiency_food$_{rot}$..

$$\begin{aligned} var\_N\_demand\_food_{rot} & \\ \leq{} & (var\_N\_supply\_residue_{rot} - var\_N\_supply\_residue\_feed_{rot}) \\ & + var\_N\_supply\_manure\_food_{rot} + var\_legume\_food_{rot} \\ & + var\_deposition\_food_{rot} + (uptake\_eff * var\_N\_fert\_food_{rot}) \end{aligned}$$

$\forall rot|\ rot\neq"R4"$

e_N_sufficiency_feed$_{rot}$..

$$\begin{aligned} var\_N\_demand\_feed_{rot} & \\ \leq{} & var\_N\_supply\_residue\_feed_{rot} + var\_N\_supply\_manure\_feed_{rot} \\ & + var\_legume\_feed_{rot} + var\_deposition\_feed_{rot} + (uptake\_eff \\ & * var\_N\_fert\_feed_{rot}) \end{aligned}$$

$\forall rot|\ rot\neq"R4"$

e_N_residue_constraint..

$$var\_N\_supply\_residue\_feed_{rot} \leq var\_N\_supply\_residue_{rot}$$

$\forall rot|\ rot\neq"R4"$

e_N_input_legume..

$$\mathrm{var\_N\_input\_legume} = \mathrm{var\_N\_demand}_{"R4"} - var\_deposition_{"R4"}$$

Note: var_deposition$_{"R4"}$ is subtracted from var_N_demand$_{"R4"}$ because var_N_demand$_{"R4"}$ is negative due to the N fixed by lucerne.

Where,

$$var\_VEM\_production_{feed\_crop,rot} = VEM_{feed\_crop} * Y_{feed\_crop} * DM\_frac\_feed_{feed\_crop} * crop\_freq\_feed_{feed\_crop,rot} * var\_X_{rot} \qquad \forall\, feed\_crop,rot$$

$$var\_DVE\_production_{feed\_crop,rot} = DVE_{feed\_crop} * Y_{feed\_crop} * DM\_frac\_feed_{feed\_crop} * crop\_freq\_feed_{feed\_crop,rot} * var\_X_{rot} \qquad \forall\, feed\_crop,rot$$

$$var\_N\_demand\_food_{rot} = \sum_{food\_crop} \left(var\_X_{rot} * N\_req\_food_{food\_crop} * crop\_freq\_food_{food\_crop,rot}\right) \qquad \forall\, rot$$

$$var\_N\_demand\_feed_{rot} = \sum_{feed\_crop} \left(var\_X_{rot} * N\_req\_feed_{feed\_crop} * crop\_freq\_feed_{feed\_crop,rot}\right) \qquad \forall\, rot$$

$$var\_N\_demand\_legume = var\_X_{"R4"} * crop\_freq\_legume_{"\mathrm{Lucerne}","R4"} * N\_legume$$

$$var\_N\_supply\_residue_{rot} = \sum_{food\_crop} \big(uptake\_eff * var\_X_{rot} * crop\_freq\_food_{food\_crop,rot} * NFRV\_residue * N\_residue\_food_{food\_crop}\big) + \sum_{feed\_crop} \left(uptake\_eff * var\_X_{rot} * \frac{crop\_freq\_feed_{feed\_crop,rot}}{crop\_period_{feed\_crop}} * NFRV\_residue * N\_residue\_feed_{feed\_crop}\right)$$

$$\forall rot | rot \neq "R4"$$

$$var\_N\_supply\_manure\_food_{rot} = uptake\_eff * (1 - N\_manure\_loss) * var\_N\_manure\_food_{rot} * NFRV\_manure$$

$$\forall rot | rot \neq "R4"$$

$$var\_N\_supply\_manure\_feed_{rot} = uptake\_eff * (1 - N\_manure\_loss) * var\_N\_manure\_feed_{rot} * NFRV\_manure$$

$$\forall rot | rot \neq "R4"$$

$$var\_N\_supply\_legume = \mathrm{uptake\_eff} * \mathrm{var\_X}_{"R4"} * crop\_freq\_legume_{\mathrm{"legume"}, "R4"} * \mathrm{NFRV\_residue} * \mathrm{RYG\_lucerne} * \mathrm{N\_residue\_legume}_{"lucerne"}$$

$$var\_deposition\_food_{rot} = \sum_{food\_crop} (crop\_freq\_food_{food\_crop,rot}) * var\_X_{rot} * deposition * uptake\_eff$$

$$\forall rot$$

$$var\_deposition\_feed_{rot} = \sum_{feed\_crop} (crop\_freq\_feed_{feed\_crop,rot}) * var\_X_{rot} * deposition * uptake\_eff \qquad \forall\, rot$$

$$var\_N\_fert\_food_{rot} = \frac{1}{uptake\_eff} * (var\_N\_demand\_food_{rot} - (var\_N\_supply\_residue_{rot} - var\_N\_supply\_residue\_feed_{rot}) - var\_legume\_food_{rot} - var\_N\_supply\_manure\_food_{rot} - var\_deposition\_food_{rot}) \qquad \forall rot$$

$$var\_N\_fert\_feed_{rot} = \frac{1}{uptake\_eff} * (var\_N\_demand\_feed_{rot} - var\_N\_supply\_residue\_feed_{rot} - var\_legume\_feed_{rot} - var\_N\_supply\_manure\_feed_{rot} - var\_deposition\_feed_{rot}) \qquad \forall rot$$

$$var\_deposition\_legume = crop\_freq\_legume_{\text{"legume"},\text{"}R4\text{"}} * var\_X_{\text{"}R4\text{"}} * deposition$$

$$var\_X_{rot} \geq 0, var\_N\_fert \geq 0, var\_VEM\_production \geq 0, var\_DVE\_production \geq 0$$

Post-optimization calculations

Parameter	Description	Unit
people_per_ha	Number of people sustained per hectare without correction	people ha^{-1}
animals_per_ha	Number of animals sustained per hectare without correction	cows ha^{-1}
num_cows	Number of cows	# cows
ProtSupplyMilk	Protein production in milk	kg Protein
ProtSupplyBeef	Protein production in beef	kg Protein
ProtsupplyVeal	Protein production in veal	kg Protein
$prot\_food_{food\_crop}$	Protein content per food crop	kg Protein ton DM^{-1}
kjeldahl	Factor to convert protein contents of meat and food crop products to N contents	kg Protein kg N^{-1}
kjeldahl_milk	Factor to convert protein content of milk to N content	kg Protein kg N^{-1}
N_dairy	N output in milk and meat	kg N
N_food	N output in food crops corrected for surpluses	kg N
N_input	N inputs to the system corrected for surpluses	kg N
OI_ratio	N- Output/Input ratio	kg N output kg N input^{-1}
$fraction\_VEM_{feed\_crop}$	Share of each feed_crop to the total VEM production	-
$surplus\_land\_feed_{feed\_crop}$	Land required to produce surplus feed_crop	ha
$food\_surplus_{food\_crop}$	Amount of surplus food_crop produced	ton FM
$surplus\_land\_food_{food\_crop}$	Land required to produce surplus food_crop	ha
corrected_land_human	Land required to produce exactly as much food and feed as is needed food and dairy demands along with land used to grow lucerne	ha
people_per_ha_corrected	Number of people sustained per hectare with correction for surpluses	people ha^{-1}
animals_per_ha_corrected	Number of cows sustained per hectare with correction	cows ha^{-1}

P_BNF_GC_trans_soil	Proportion of N fixed by clover, transferred to the soil	-
N_credit_legume	N fixed by field peas and fava beans, available to the next crops	-
DM_frac_food(food_crop)	Dry matter fraction of food_crop	ton DM ton FM^{-1}
food_feed_surplus_correction(rot)	Total land required after correcting for food and feed surpluses, per rotation	ha
lucerne_contribution(rot)	Contribution of lucerne to meet N demands per rotation	-
N_demand_ha(rot)	Total N demand per hectare of each rotation	kg N ha^{-1}
lucerne_correction	Corrected amount of land used to grow lucerne	ha
N_surplus_ha	N input per hectare that is not available to any crop	kg N ha^{-1}
N_fert_ha	Mineral fertilizer used per hectare	kg N ha^{-1}
N_fert_ha_corrected	Mineral fertilizer used per hectare after correction for surpluses	kg N ha^{-1}
N_fert_contribution$_{rot}$	Share of N_demands of a rotation met by mineral fertilizer	-
N_fert_correction$_{rot}$	Mineral fertilizer used per rotation after correcting for surpluses	kg N ha^{-1}

Note: The suffix ".L" denotes the current value of the variable or equation after optimisation.

Where,

$$fraction\_VEM_{feed\_crop} = \sum_{rot} \frac{var\_VEM\_production_{feed\_crop,rot}}{e\_VEM.L}$$

$$\forall feed\_crop$$

$$surplus\_land\_feed_{feed\_crop} = \frac{fraction\_VEM_{feed\_crop} * (e\_VEM.L - e\_VEM.LO)}{Y\_feed_{feed\_crop} * DM\_frac\_feed_{feed\_crop} * VEM_{feed\_crop}}$$

$$\forall feed\_crop$$

$$animals\_per\_ha = \frac{num\_cows}{\sum_{feed\_crop,rot} var\_X.L_{rot} * crop\_freq\_feed_{feed\_crop,rot}}$$

$$\mathit{animals\_per\_ha\_corrected} = \frac{\mathit{num\_cows}}{\sum_{\mathit{feed\_crop,rot}} \mathit{crop\_freq\_feed}_{\mathit{feed\_crop,rot}} * \left(\mathit{var\_X}.L_{\mathit{rot}} - \mathit{surplus\_land\_feed}_{\mathit{feed\_crop}}\right)}$$

$$\mathit{food\_surplus}_{\mathit{food\_crop}} = \mathit{e\_human\_nutrition}.L_{\mathit{food\_crop}} - \mathit{e\_human\_nutrition}.LO_{\mathit{food\_crop}} \qquad \forall \mathit{food\_crop}$$

$$\mathit{surplus\_land\_food}_{\mathit{food\_crop}} = \frac{\mathit{food\_surplus}_{\mathit{food\_crop}}}{\mathit{Y\_food}_{\mathit{food\_crop}}} \qquad \forall \mathit{food\_crop}$$

$$\begin{aligned} \mathit{food\_feed\_surplus\_correction}_{\mathit{rot}} &= \sum_{\mathit{food\_crop}} (\mathit{crop\_freq\_food}_{\mathit{food\_crop,rot}} \\ &* \left(\mathit{var\_X}.L_{\mathit{rot}} - \mathit{surplus\_land\_food}_{\mathit{food\_crop}}\right) \\ &+ \sum_{\mathit{feed\_crop}} (\mathit{crop\_freq\_feed}_{\mathit{feed\_crop,rot}} \\ &* \left(\mathit{var\_X}.L_{\mathit{rot}} - \frac{\frac{\mathit{var\_VEM\_production}.L_{\mathit{feed\_crop,rot}}}{\mathit{e\_VEM}.L} * (\mathit{e\_VEM}.L - \mathit{e\_VEM}.LO)}{\mathit{Y\_feed}_{\mathit{feed\_crop}} * \mathit{DM\_frac\_feed}_{\mathit{feed\_crop}} * \mathit{VEM}_{\mathit{feed\_crop}}} \right) \end{aligned} \qquad \forall \mathit{rot}$$

$$\mathit{lucerne\_contribution}_{\mathit{rot}|\mathit{var\_X}.L_{"R4"}>0} = \frac{\mathit{var\_legume\_food}.L_{\mathit{rot}} + \mathit{var\_legume\_feed}.L_{\mathit{rot}}}{\mathit{var\_N\_demand\_food}.L_{\mathit{rot}} + \mathit{var\_N\_demand\_feed}.L_{\mathit{rot}}} \qquad \forall \mathit{rot}$$

$$\mathit{N\_demand\_ha}_{\mathit{rot}} = \frac{\mathit{var\_N\_demand\_food}.L_{\mathit{rot}} + \mathit{var\_N\_demand\_feed}.L_{\mathit{rot}}}{\mathit{var\_X}.L_{\mathit{rot}}} \qquad \forall \mathit{rot}$$

$$\mathit{lucerne\_correction} = \frac{\sum_{\mathit{rot}} \mathit{var\_X}.L_{"R4"} * \mathit{food\_feed\_surplus\_correction}_{\mathit{rot}} * \mathit{N\_demand\_ha}_{\mathit{rot}} * \mathit{lucerne\_contribution}_{\mathit{rot}}}{\mathit{var\_N\_supply\_legume}.L}$$

$$\mathit{corrected\_land\_human} = \sum_{\mathit{rot}} (\mathit{food\_feed\_surplus\_correction}_{\mathit{rot}}) + \mathit{lucerne\_correction}$$

$$\mathit{people\_per\_ha} = \frac{\mathit{num\_people}}{\mathit{var\_X\_total}.L}$$

$$\mathit{people\_per\_ha\_corrected} = \frac{\mathit{num\_people}}{\mathit{corrected\_land\_human}}$$

$$N\_dairy = \frac{ProtSupplyMilk}{kjeldahl\_milk} + \frac{ProtSupplyMilk + ProtSupplyBeef}{kjeldahl}$$

$$N\_fert\_ha = \sum_{rot} \frac{var\_N\_fert\_food.L_{rot} + var\_N\_fert\_feed.L_{rot}}{var\_X\_total.L}$$

$$\begin{aligned} & N\_fert\_contribution_{rot|var\_X.L_{rot}>0} \\ & \quad = \frac{uptake\_eff * (var\_N\_fert\_food.L_{rot} + var\_N\_fert\_feed.L_{rot})}{var\_N\_demand\_food.L_{rot} + var\_N\_demand\_feed.L_{rot}} \end{aligned}$$

$$\begin{aligned} & N\_fert\_correction_{rot|var\_X.L_{rot}>0} \\ & \quad = \frac{var\_N\_demand\_food.L_{rot} + var\_N\_demand\_feed.L_{rot}}{var\_X.L_{rot}} \\ & \quad * N\_fert\_contribution_{rot} * food\_feed\_surplus\_correction_{rot} \end{aligned}$$

$$N\_fert\_ha\_corrected = \frac{\sum_{rot} N\_fert\_correction_{rot}}{\sum_{rot}(food\_feed\_surplus\_correction_{rot}) + lucerne\_correction}$$

$$\begin{aligned} N\_input = & \sum_{rot}(N\_fert\_correction_{rot}) + \Bigg(deposition \\ & * \left(\sum_{rot}(food\_feed\_surplus\_correction_{rot}) + lucerne\_correction \right) \Bigg) \\ & + \sum_{rot} \Bigg(food\_feed\_surplus\_correction_{rot} * \frac{|N\_req\_feed_{\text{Grass\_clover}}|}{P\_BNF\_GC\_trans\_soil} \\ & * crop\_freq\_feed_{\text{"Grass\_clover"},rot} \Bigg) \\ & + \Bigg(\sum_{food\_crop,rot|food\_crop=\text{"Field\_pea"OR "}Fava\_bean\text{"}} |N\_req\_food_{food\_crop}| \\ & * food\_feed\_surplus\_correction_{rot} \\ & * crop\_freq\_food_{\text{food\_crop},rot})/N\_credit\_legume + (|N\_legume| \\ & * lucerne\_correction) \end{aligned}$$

$$OI\_ratio = \frac{N\_dairy + N\_food}{N\_input}$$

$$
\begin{aligned}
N\_surplus\_ha = (&\left|\sum_{rot} e\_N\_sufficiency\_food.L_{rot} + e\_N\_sufficiency\_feed.L_{rot}\right| \\
&+ \sum_{rot|rot\neq"R4"} \left(\frac{var\_N\_supply\_residue.L_{rot}}{uptake\_eff * NFRV\_residue} * (1 - uptake\_eff) \right. \\
&\left. * (1 - NFRV\_residue)\right) \\
&+ \big((var\_N\_manure\_food.L_{rot} + var\_N\_manure\_feed.L_{rot}) * (1 - uptake\_eff) \\
&* (1 - NFRV\_manure) * \ N\_manure\_loss)\big) \\
&+ \big((1 - uptake\_eff) * (var\_N\_fert\_food.L_{rot} + var\_N\_fert\_feed.L_{rot})\big) \\
&+ \left(\frac{var\_deposition\_food.L_{rot} + var\_deposition\_feed.L_{rot}}{uptake\_eff} * (1 - uptake\_eff) \right. \\
&\left. * (1 - NFRV\_residue)\right) + |var\_N\_input\_legume.L|)/\ var\_X\_total.L
\end{aligned}
$$