Leys in sustainable farming systems

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Abstract

A grass ley is defined as a temporary grassland that is integrated in a crop rotation. It has its origin in the 16th century in Brabant and Flanders, where red clover replaced the fallow period in the crop rotation. Today, the main reasons for the use of leys have remained very similar; next to weed and pest control, leys are used for improving soil quality, fertilisation and feed for livestock. Where leys originally consisted of mainly red clover, they have evolved to leys with lucerne, grasses and mixtures with grass-clover and grass-clover with forbs. *Grosso modo*, three types of farming systems in which leys are used can be distinguished: (1) dairy/beef farming systems with leys in rotation with fodder crops; (2) mixed dairy/beef and arable farming systems (on one farm or regionally cooperating farms) using leys in the arable rotation for forage or biomass for energy; and (3) arable farming systems using leys for internal input as cut and carry fertilizers (C&C) or 'green fertilizer'. In this paper these three types of farming systems are described and illustrated with case studies. The role of a ley, consequences for species choice, ley duration and percentage of leys in the system are discussed.

Keywords: temporary grassland, crop rotation, integrated crop-livestock systems, cut and carry fertilizers, ecosystem services

Introduction

In the dictionary, the term ley, lea or lay is described as 'arable land laid down for grassland'. Allen *et al.* (2011), define a grass ley as a temporary grassland that is integrated in a crop rotation. A temporary grassland is composed of annual, biennial, or perennial forage species kept for a short period of time (usually only a few years) (Allen *et al.*, 2011). Temporary grassland in the EU is defined as grassland included as a part of a normal crop rotation, lasting at least one crop year and for less than five years (Lesschen *et al.*, 2014). Therefore, according to EU definitions, all temporary grasslands are leys.

In this paper we first go into the history of leys. Subsequently we describe the main motivations for the use of leys and which ecosystem services they provide and how this affects the choice of species. *Grosso modo*, three types of farming systems in which leys are used can be distinguished: (1) dairy/beef farming systems with leys in rotation with fodder crops; (2) mixed dairy/beef and arable farming systems (on one farm or regionally cooperating farms) using leys in the arable rotation for forage or biomass for energy; and (3) arable farming systems using the harvest of leys directly or harvested as silage for internal input as fertilizer the so called cut and carry fertilizers (C&C). In this paper these three types of farming systems are described and illustrated with case studies. The role of a ley, consequences for species choice, ley duration and percentage of leys in the system are discussed.

Historical perspective

A first record of a ley as an integral part of the crop rotation is from the 16th century in the Low Countries, Brabant and Flanders, now situated in Belgium. In the Low Countries, red clover (*Trifolium pratense*) structurally replaced the fallow period in the three-course crop rotation and changed it to a four-course rotation (Blom *et al.*, 2006; Peeters, 1980). This was also observed by the English writer Sir Richard Weston during his exile in the Low Countries in 1644-45, who wrote this in his account 'A Discours of Husbandrie used in Brabant and Flanders: shewing the wonderful Improvement of Land there; and serving as a Pattern for our Practice in this Common-Wealth' (Weston, 1652). This account is one of the first descriptions of the use of a farming rotation including (red) clover. The Norfolk four-course rotation with a red clover ley became the cornerstone of the 'agricultural revolution' in the 18^{th} century, very well described in Kjærgaard (1994, 2003).

After the second world war the combination of the use of mineral fertilizers, pesticides, high-yield crop varieties, mechanisation, and government policies, subsidies and grants improved productivity. A ley crop rotation in a mixed farming system became of less importance and further agricultural specialisation and intensification was a fact (Knox *et al.*, 2011; Robinson and Sutherland, 2002). In Belgium, 4.6% of the agricultural area was covered with different species of clovers in 1929 (Atlas). The area started to decline quickly from 1935 onwards, to reach about 0.1% of the agricultural area in 2000. In the Netherlands, the area of clover and lucerne (*Medicago sativa*) on arable land reduced from 9% just after the second world war to 1% at present (CBS Statline). At the same time there was an increase in the area of temporary grassland on specialised dairy and beef farms in The Netherlands from 4% in 1970 to 11% in 2000, which peaked at 20% and 26% in 2003 and 2015, respectively, when EU regulations on permanent grassland were formalised (CBS Statline). Probably it was the formalisation of the regulations itself, which made farmers more aware about the difference between permanent and temporary grassland, which made both categories to be more carefully registered. Temporary grassland covered 6% of the agricultural land in Belgium in the period 2015-2019; permanent grassland covered 34% and silage maize (*Zea mays*) 12% (Statbel, 2008). On Danish dairy farms, in 2015-2019, 28% of the agricultural land was used for temporary grassland (predominantly grass-clover), 7% was permanent grassland and 24% was silage maize (Kristensen *et al.*, 2020). The average duration of the temporary grasslands was short, only three years on average due to a general yield and quality decline with grassland age (Eriksen *et al.*, 2012; Kristensen *et al.*, 2022).

At present, the 'From Farm to Fork' policy of the EU with, among others, plans for reductions in the use of pesticides (-50%) and fertilizers (-20%), combined also with an increase in fertilizer prices due to the Ukraine war, call for management practices that can support this. The use of leys is one of these management practices. In the recent decades, there is already a revival of leys as a management practice in sustainable farming systems including organic, agro-ecological and regenerative farming (Erisman *et al.*, 2016; Schreefel *et al.*, 2020).

Motivations and ecosystem services

Initially, the use of leys in the 16^{th} century was aimed at improving soil fertility specifically and soil quality in general, with reduction of weeds and pests, and providing feed for livestock for recycling manure, but also as feed for horses and oxen for animal traction. Today, motivations for the use of leys remain essentially the same. However, in addition to the aims listed above, new motivations have arisen. For example, food for pollinators and other insects has now become an explicit objective of leys, whereas in the past the role of flowering leys of clover and lucerne in the crop rotation was merely a side-effect. Also, functions like climate regulation, water purification and phyto-extraction of residues of pesticides in the soil were not necessary or valued at that time (Martin *et al.*, 2020; Van Eekeren *et al.*, 2022).

The motivations of the past can be translated into ecosystems services in the present. Ecosystem services are the benefits that people derive from ecosystems to meet physiological, economic and non-material needs (MEA, 2005). Recently, Coolidge *et al.* (2022) and Martin *et al.* (2020) have provided an extensive review of the benefits and ecosystem services of leys in future farming systems. Martin *et al.* (2020) distinguish services flowing to crop production (input services more or less equivalent to regulating and maintenance services) and those flowing from crop production (output services more or less equivalent to provisioning services). Among input services they consider; soil conservation, nutrient provision and recycling, soil water retention, and biological control of pests and weeds. The main output services identified are: water purification, climate regulation, habitat provision for biodiversity conservation, and production of forage for livestock (both quantity and quality) or biomass to produce energy or C&C fertilizers. These services can be on field, farms, landscape, watershed and global level. In addition to these services, Martin *et al.* (2020) discuss the potential negative impact of leys including the competition for land with food crops and the increase in GHG emissions when leys are fed to ruminants.

Species and mixtures used

The composition of leys varies depending on region and the main motivation(s) or ecosystem service(s). They can consist of monocultures or mixtures of different grass, legume and forb species. For grasses, often grasses like perennial (*Lolium perenne*) and Italian ryegrass (*Lolium multiflorum*) are used because of their wide tolerance to different conditions, versatility of use (silage, hay and grazing), and high digestibility for livestock (Kingston-Smith *et al.*, 2013), but also their positive effect on weed suppression and soil structure in monoculture or in mixture with legumes (Connolly *et al.*, 2018; De Haas *et al.*, 2019; Van Eekeren *et al.*, 2008). Legumes grown in monoculture or in mixture have the benefit of reducing the need for mineral nitrogen (N) fertilizers as a result of their N-fixing abilities (Anglade *et al.*, 2015; Hoekstra *et al.*, 2017; Nyfeler *et al.*, 2009, 2011) but can also have positive effects on aboveground and belowground biodiversity (De Haas *et al.*, 2019; Van Eekeren *et al.*, 2008). For a further increase in resilience and ecosystem services forbs can be included in mixtures with grass and legumes (Cong *et al.*, 2017, 2018).

In an experiment in the Netherlands, the potential effects of different grass-clover mixtures and monocultures in an (organic) arable crop rotation on below- and aboveground traits and services were investigated. The experiment included two grasses (perennial and Italian rye grass) and two clovers (red and white clover (*Trifolium repens*)) in monocultures and mixtures. The grass monocultures showed high root density, good weed suppression and perennial ryegrass especially had a positive effect on soil structure (Table 1). Clover on the other hand had a positive effect on the soil mineral N, and earthworm abundance tended to be higher in the clover monocultures. Moreover, clover showed high herbage dry matter yield (particularly red clover) and N yield, and white clover showed high digestibility. When (some of) the four species were combined in grass-clover mixtures, they combined the positive effects of the species and often even outperformed the (best) monocultures (De Haas *et al.*, 2019). These results are in line with the findings of Finn *et al.* (2012, 2013).

The integration of leys in farming systems

We define three types of farming systems in which leys can be used. In the following sections we will give a general description of leys in each of these three farming systems, followed by a case study.

1. Dairy/beef farming systems with leys in rotation with fodder crops

Most specialised dairy and beef farms in North-West Europe combine grassland and arable land for cultivation of silage maize and, to a lesser extent, cereals for whole crop silage and fodder beet. In most cases, silage maize is permanently cultivated (year after year on the same field). Permanent cultivation of silage maize on the same production area leads to soil fertility problems, nitrate leaching and a possible decline in production. Long term research on the effect of ley-arable rotations compared with permanent grassland and arable land in the Woburn experiment in Rothamsted (Johnston *et al.*, 2017) and on the M66-1 experiment on a sandy loam soil in Melle (Nevens and Reheul, 2001, 2002, 2003; Van Eekeren *et al.*, 2008) have shown that the rotation of three years grass white clover, succeeded by three years of silage maize is optimal both for productivity as well as for N-use efficiency and soil quality. In the ley-arable rotation in Melle, soil parameters including soil organic matter (SOM) and N-total showed values

Table 1. Relative score (worst performing (--), best performing (++)) of the indicators used to assess ecosystem services for different grass and clover monocultures and mixtures (Lp = *Lolium perenne L.*, Lm = *Lolium multiflorum Lam*, Tp = *Trifolium pratense L.*, Tr = *Trifolium repens L.*) (adapted from De Haas *et al.*, (2019).[1]

Ecosystem service	Fallow	Monocultures				Mixtures					Range
		Lp	Lm	Tp	Tr	Lp:Tp	Lm:Tp	Lp:Tr	Lp:Tp:Tr	4s	
Soil conservation and water retention											
Soil structure (% crumbs)	--	+/-	--	+/-	--	+	+/-	++	++	++	10-50
Root score[2]	--	++	+	+/-	+/-	++	++	++	++	++	0-8
Nutrient provision and cycling											
Soil mineral N (kg N ha^{-1})	-	--	-	++	++	-	+/-	+	+/-	+/-	57-136
Biological control of pests and weeds											
Weed suppression (% weed cover)	n.d.	+/-	++	--	--	+/-	++	+	+	+	0-11
Habitat provision for conserving associated biodiversity											
DMY in spring[3] (t ha^{-1})	n.d.	+/-	--	++	++	+/-	--	+/-	+/-	--	1.5-8.4
Soil biota 0-25 cm[1]	+/-	--	-	++	++	+	++	++	+	++	3.0-8.5
Soil biota 25-45 cm[1]	--	+	+	+	++	++	++	+	++	++	0.0-7.0
Earthworm density (n m^{-2})	--	-	+/-	+	++	+	-	++	++	+	113-994
Forage production and quality											
Herbage DMY (t ha^{-1} yr^{-1})	n.d.	--	+/-	+	+/-	++	++	+	++	++	5.9-15.9
N conc. (g N kg^{-1} DM)	n.d.	--	--	++	++	+/-	--	+/-	+/-	-	11.4-37.9
N yield (kg N ha^{-1})	n.d.	--	--	++	+	++	+/-	+	+	+/-	77-475
Digestibility (g kg^{-1} DM)	n.d.	+/-	--	-	++	-	--	+/-	-	-	633-801
DOM yield (t ha^{-1})	n.d.	--	+/-	+	+	++	+	+	++	++	4.2-10.8

[1] DM = dry matter; DMY = dry matter yield; DOM = digestible organic matter.

[2] Score out of 10.

[3] Relatively low herbage mass in spring is important for meadowbird chick development and survival. n.d. = not determined.

that were in between the values of permanent grassland and permanent arable land (Table 2). There were more roots and a greater root biomass up to a depth of 20 cm in temporary grassland compared to permanent grassland, which improves the drought tolerance of temporary grassland above permanent grassland (Reheul *et al.*, 2007). Indicators for soil structure were comparable in permanent and temporary grassland. Soil structure and earthworm biomass declined in the arable stage, but recovered when rotated with temporary grassland (Van Eekeren *et al.*, 2008).

Case study 1: Dairy systems with 60% permanent grassland and 20% three-year lasting leys with grass-clover in rotation with 20% arable land (60%-20%-20% system)

Due to EU-legislation for derogation, until 2022 the land use of most conventional dairy farms on sandy soils in the Netherlands consisted of 80% grassland and 20% arable land, with the latter mainly consisting of silage maize cultivated year after year on the same area. Based on the results of the experiments at Rothamsted and Melle, and taking into account all the challenges of the dairy industry such as the need for improving soil quality, reducing the use of artificial fertilizer and soya, reducing the emissions of greenhouse gasses (GHG), ammonia and nitrate, increasing biodiversity and keeping up the EU legislation of permanent grassland, a land use of 60% permanent grassland, and 20% three-year lasting leys with grass-clover (red and white) in rotation with 20% arable land was proposed (60%-20%-20% system).

Table 2. Mean soil chemical, physical and biological characteristics of 36-39 years of permanent grassland (PG), temporary grassland (TG, grass white clover ley), temporary arable land (TA) and permanent arable land (PA) (Van Eekeren *et al.*, 2008).[1]

	Units	Treatments					Year	Treat.×year
		PG	TG	TA	PA	*P*-value	*P*-value	*P*-value
SOM[2]	g kg dry soil^{-1}	60.7 a	33.2 b	34.9 b	21.1 c	<0.001	0.004	0.003
N-total[2]	g N kg dry soil^{-1}	2.95 a	1.52 b	1.61 b	0.95 c	<0.001	<0.001	NS
Soil structure 0-10 cm[1]								
Crumb	%	33 a	32 a	8 b	8 b	<0.001	-	-
Earthworms[2]								
Total biomass	g m^{-2}	166 a	52 b	14 bc	5 c	<0.001	NS	NS
Grass roots[3]								
20 cm depth	n m^{-2}	1,081 b	1,813 a	-	-	<0.008	-	-

[1] Values followed by the same letter within a row are not statistically different at the 5% error level for the main treatment effect. NS = not significant.

[2] Means of 2002, 2003 and 2004. SOM = soil organic matter.

[3] Measured in 2004 only.

The impact on economics and environmental parameters of the change of the common land use (80% permanent grassland and 20% permanent arable land) to the 60%-20%-20% system was calculated with the model BBPR (De Boer, 2007). Calculations were based on an average farm in the east of The Netherlands on sandy soils: 100 dairy cows with accompanying young stock, 850,000 kg of milk on 47.2 ha of land. The land is structured as 60% (28.3 ha) permanent grassland close to the farm and a field plot of 18.8 ha at some distance from the farm buildings. The permanent grassland is used for mixed grazing/mowing management. On the field plot, 50% (9.4 ha) of the area (which is permanent grassland in the current situation), is sown with a mixture of perennial ryegrass, red and white clover in a three-year rotation with silage maize (instead of permanent silage maize in the current situation). On this ley, the nitrogen application rate is reduced from 242 kg N ha^{-1} (current rate on permanent grassland for mowing) to 54 kg available N ha^{-1}. Taking advantage of the N-mineralisation of the ploughed ley, the maize in rotation with the ley receives no fertilizer nitrogen in the first year of the rotation, half of the currently recommended 147 kg N ha^{-1} for permanent silage maize in the second year and full fertilizer application in the third year. Due to the halving of the N-application from slurry, an extra potassium application is necessary. The model showed that this change in land-use resulted in an increase in labour revenue by €7,400 with low fertilizer prices and by €12,175 with high fertilizer prices (Table 3). Because the gross herbage yield of the ley increases by more than 2 Mg DM ha^{-1}, less silage maize is needed and the roughage costs fall by more than €4,700. Due to the higher proportion of grass in the diet, the input of soya can be reduced, resulting in a reduction in concentrate costs of almost €4,000. Due to a higher crude protein (CP) content in the ration, the costs for slurry export of the farm increase by €2,100. Due to the nitrogen fixation, the costs for nitrogen fertilizer decrease by approximately €2,500 and €7,500 for low and high fertiliser prices respectively. However, the costs for potash fertilizer increase because less slurry is used. The costs for seed increase by almost €300 because grass-clover seed is €70 ha^{-1} more expensive than grassland and more than 3 ha grass-clover has to be sown every year. By spreading less nitrogen fertilizer, the nitrate leaching at farm level is lower than in the current situation (from 24.0 to 22.2 mg $NO3^{-}$ l^{-1}). The increase in ammonia emissions remains limited, although more CP in the ration (and therefore more N in the slurry) still leads to slightly higher ammonia emissions compared to the baseline situation (+1.6 kg $NH3^{+}$ ha^{-1}) (Van Eekeren *et al.*, 2016).

Table 3. Economy of the current average dairy farm with 80% permanent grassland and 20% permanent arable land with silage maize, and the difference when the land use is changed towards 60% permanent grassland, and 20% three-year grass-clover ley in rotation with 20% arable land with silage maize (adapted from Van Eekeren *et al.*, 2016).

	Current situation	**Difference with current situation when changed to 20% grass-clover leys**	
Fertilizer N price	Low	Low	High
Revenue from milk, etc. (A)	€342,865	+€0	+€0
Allocated costs (B)	€124,231	-€10,297	-€15,029
- Concentrate	€54,340	-€3,950	-€3,950
- Roughage and other feed	€21,536	-€4,686	-€4,866
- Nitrogen fertilizer	€6,515	-€2,565	-€7,624
- Potassium fertilizer	€1,442	+€646	+€974
- Seed	€2,961	+€278	+€278
Non allocated costs (C)	€228,401	+€2,854	+€2,854
- Contract work	€36,840	+€583	+€583
- Slurry export	€7,688	+€2,145	+€2,145
- General	€17,300	+€0	+€0
Labour revenue (A – B – C)	€-9,767	+€7,443	+€12,175

[1] Calculations with a low and high fertilizer N price are shown (€1.10 and €3.27 per kg N-fertilizer, respectively).

2. Mixed dairy/beef and arable farming systems using leys in the arable rotation

Although mixed livestock-crop systems at farm level have decreased in Europe, in practice examples can still be found, and leys have an important function in these systems. For example, the leys on an arable farm may be grazed by livestock owned by arable or livestock farmers. On a larger scale, arable farms may sell the harvested herbage for fodder or biomass, or leys may be contract-grown by companies that look after the growing and harvest. This is practised for example with lucerne, which is artificially dried and used as concentrates or other livestock feeds. On the other hand, also new mixed farming systems, also referred to as integrated crop-livestock systems (ICLS), have been reintroduced to promote more climate-resilient, sustainable and economically viable farming systems, compared to specialized and intensive systems (Sekaran *et al.*, 2021). Interesting are the ICLSs in which the cooperation affects the constituent farms, in order to produce more efficiently and economically, given the natural, economic and social constraints (Schut *et al.*, 2021).

Case study 2: Partnership farms in organic farming

In the Netherlands, more and more organic arable and dairy farmers work together in a so called partner farm concept (Nauta *et al.*, 1999; De Wit *et al*, 2006): mixed farming beyond farm level with one arable farm and one to five dairy farms (on average 1.9 dairy farms) at some distance of each other (average 34 km, up to 90 km) (De Wit *et al.*, 2022). In this system, most arable farms grow short term grass-clover leys for one to two years, as fodder for dairy farms in exchange for, e.g. manure, as a way to overcome some of the major disadvantages of specialisation for organic farmers: it widens the crop rotation of the arable farms, mainly facilitating N-fixation and weed suppression, while simultaneously it secures the supply of fodder with a high protein content and digestibility to the livestock farms, both at relatively low costs given the organic preconditions. The organic arable farms are mainly interested in grass-clover mixtures rather than in wheat or maize production to be used as concentrate because of the need of N-fixation and weed suppression in the rotation related to labour shortages. Therefore, the cooperation is often with organic dairy/beef farms and not with specialised organic chicken or pig farms. Major attention is given to, e.g. appropriate grass-clover mixtures, indicating the importance of high yielding red clover, both in terms of production and weed-suppression, above white clover. The most appropriate grass component in these mixtures is less clear, as e.g. hybrid and Italian rye grass might be suitable for weed suppression but at the risk of suppressing the share of clover and hence N-fixation (De Haas *et al.*, 2019; De Wit *et al.*, 2015).

The best way to include leys in an arable cropping system remains an ongoing process, because of the continuous changes of crop proportions in a cropping system in line with dynamic demands. However, an evaluation after 15 years showed that most arable farms cooperating in an ICLS, had devoted 25-40% of their agricultural area to grass-clover leys. This was in line with impact calculations with the model FARMDesign (Groot *et al.*, 2012) that indicate that high economic returns are still possible if 1/3rd of the crop rotation consists of grass-clover, while lower shares of grass-clover in the crop rotation might be hampered by labour constraints (e.g. weed control) or too low N-surpluses to support high yielding cash crops (Figure 1) (De Wit *et al.*, 2022). With such ICLS beyond farm level, decision making on livestock and crops is split into separate entities with different persons, incurring many socio-psychological issues. In their evaluation, participating farmers ranked the ease of communication as most important, followed by perceived reliability and potential for a long-term cooperation (De Wit *et al.*, 2022). In conclusion, the evaluation showed that partner farms can be characterized as informal but market-oriented 'business partnerships', based on the exchange of high valued materials as well as enhanced ecosystem services of leys.

3. Arable farming systems using leys on their own farm as C&C fertilizers

The objective of arable farming systems using leys as C&C fertilizers is to develop intensive cropping systems that facilitate more effective use of on-farm N-fixation (Antichi *et al.*, 2008). This was achieved by developing cropping systems based on leys of grass-clover or lucerne used as fertilizer (Van der Burgt *et al.*, 2013). Nutrients accumulated by these leys can be used as C&C fertilizer without being sold off-farm as forage and passing through an animal. This is desirable because the revenues from these crops are rather limited, whereas the on-farm nutrient-use efficiency on these organic arable farms can be improved. On top of this, the nutrients in these crops are better balanced for crop growth than the nutrients available in animal manure. In experiments, C&C fertilizers based on lucerne or clover have shown to be at least as efficient as animal manure in terms of N supplying capacity (Sorensen and Thorup-Kristensen 2011; Van der Burgt *et al.*, 2013). Although this form of use of leys started out as an extra way to use the product of leys next to forage, it is now also developing as a practice for certified vegan products cultivated without animal manure.

Case study 3: Experimental farm Kollumerwaard without external fertilizer

On the experimental farm Kollumerwaard in the North-East of the Netherlands, a field trial with an organic 6-year arable rotation based on 100% biologically fixed nitrogen without animal manure was established in 2012. The location has very fertile soil, reclaimed from the sea 50 years before, with 12% clay and 1.0% organic carbon (Van der Burgt *et al.*, 2021). The expectation was that a system relying on its own N-fixation will be strongly nitrogen-limited. To get a clear answer on the nitrogen fixation potential on the farm, no other inputs from outside the farm were used. The crop rotation and fertiliser strategy are presented in Figure 2. Each of the six crop fields is 0.8 ha, resulting in a total trial surface of 4.8 ha. The herbage produced in the ley, is a mixture of legumes (lucerne, red, white and Alexandrian clover), and harvested and conserved as silage until the next year as if it were fodder for ruminants. However, instead of feeding it to animals and using the resulting manure as fertilizer, the harvested product is directly used as C&C fertilizer. Therefore, the fluctuating yearly nitrogen production of the ley determines the N fertilizer input of the winter carrot, oats and seed potato in the following year.

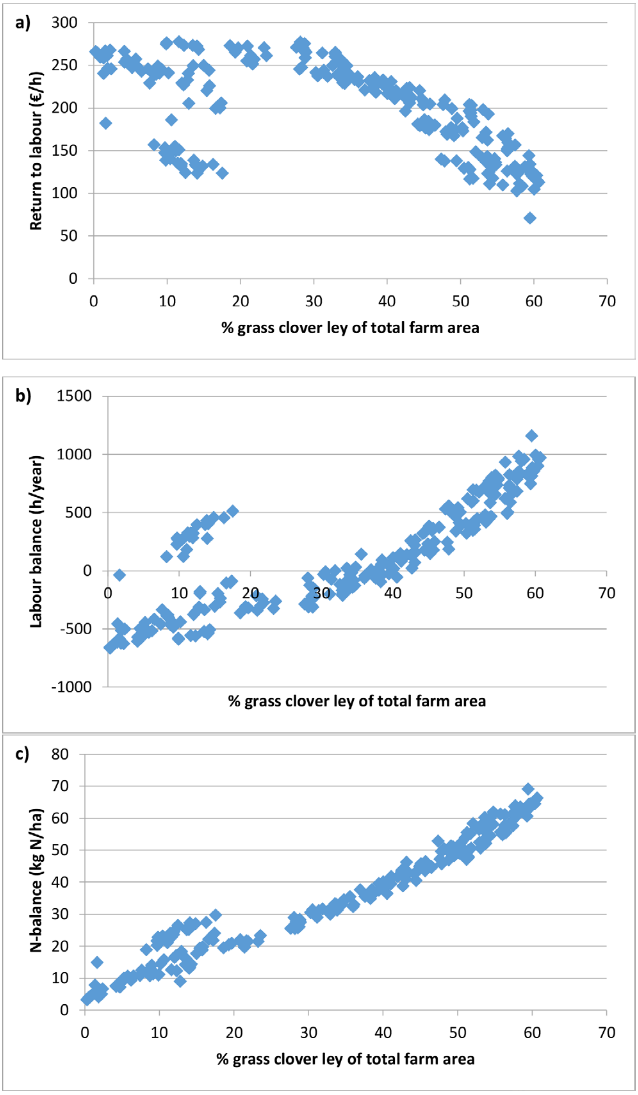

Figure 1. The effect of % grass-clover leys of the total area in the arable crop rotation on the return to labour (A), labour balance (B) and N balance (C) on the arable farm (adapted from De Wit *et al.*, 2022).

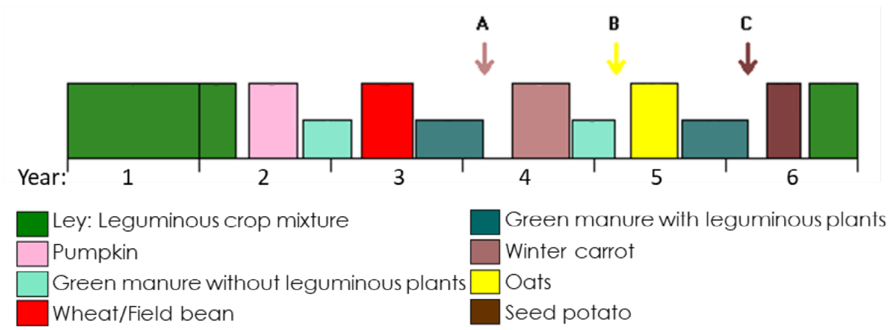

Figure 2. Six year crop rotation (see legend) and fertilizer scheme of C&C (Cut and Carry) fertilizer with arrows: (A) C&C fertilizer, 20% of C&C harvested in the year before; (B) C&C fertilizer 30%; (C) C&C fertilizer 50% (Van der Burgt *et al.*, 2021).

The yields of the different crops over nine experimental years (2012-2020) are shown in Table 4. Considered on a per hectare basis, the crop yield was not much lower (0% cereals, up to 10% seed potatoes) compared to manure-based organic production at this farm and in the region. In organic farming with manure, some crops might also be nitrogen-limited, others not (potato: *Phytophthora*-limited). However, taking into account that 1/6th of the area is needed for the C&C fertilizer, crop production on the whole farm level was at least 17% lower. The production of the C&C fertilizer was stable except for one year with an extreme low production, possibly due to drought. The wheat/field bean showed a strong trend to increased yield, as a result of the learning process on how to cultivate this mixed crop (variety choice, row distance, seed depth, mixed rows or separate rows). Carrot production was influenced by germination success (drought, weeds, soil structure) and weed pressure. No explanation is found for the strong increase in oats yield. Seed potato yield level was dominantly influenced by *Phytophthora*.

The nitrogen performance of the system has been evaluated by means of the NDICEA model (Van der Burgt *et al.*, 2006), which confirmed that the system is highly nitrogen-limited. There were no signs of other nutrient deficiencies. Soil nutrient stock was abundant, and during nine years only a small decrease was measured in P stock (P-AL, mg P_2O_5/100 g, -0.776 per year, P<0.01) and a considerable decrease in P availability (P-water soluble, mg P_2O_5 l^{-1}, -2.325 per year, P<0.001). Soil organic C and organic N showed no statistically significant change during the experiment, both measured and modelled. The system was highly N-efficient: N-efficiency defined as N-output/(N-fixation + N-deposition) was 76%. This high efficiency was due to very low losses: 17 kg N ha^{-1} yr^{-1} was lost due to leaching and 7 kg N ha^{-1} yr^{-1} was lost due to denitrification in the topsoil. There were no losses by volatilization since no manure or artificial fertilizer was used. N-losses in the silage process were minimal. In this system, 17% of the surface is used for C&C production, occupying space in which no cash crop can be cultivated. A higher C&C intensity could result in higher N-available levels and hence in higher potential yields of the cash crops, but the effect on the financial benefit is uncertain. This will highly depend on the availability and price of organically certified manure. If that price will go up, which is expected to occur, the C&C pathway will become more and more attractive as an additional source of nitrogen. Also, the C&C system resulted in additional costs associated with contract labour for the harvest of the C&C fertiliser (4 cuts per year). The next years' distribution was realized with own labour and equipment. Both activities result in additional costs compared to the purchase and application of manure.

Table 4. Yield level[1] of the different crops during the first nine experimental years (2012-2020) of a field trial with an organic 6-year arable rotation based on 100% biologically fixed nitrogen without animal manure (Van der Burgt *et al.*, 2021). The trend shows if the production has increased (+) over the years and if it has decreased (-) over the years measured.

	# years	Average	Minimum	Maximum	Trend
C&C fertilizer (in dry matter)	9	9,222	4,511	11,434	0
Pumpkin	7	20,665	14,400	27,181	+
Wheat/Field bean (85% d.m.)	6	4,572	2,545	8,308	++
Carrots	9	67,694	46,566	82,800	-
Oats	7	5,636	3,600	7,836	++
Seed potatoes	9	35,413	27,550	42,381	+

[1] Yield is expressed in kg fresh material ha^{-1}, except for the ley for the C&C fertilizer, which is expressed in kg dry matter ha^{-1}.

Results of this field trial show that this type of ley-based nitrogen-limited system can only perform adequately if every link in the crop rotation chain is dedicated to adding nitrogen into the system and preventing losses due to leaching, denitrification and volatilization. In the current experiment, 87% of the time a growing crop was present on the fields, and 51% of the time a legume or legume-including crop mixture was present on the field. Moreover, in ley-based nitrogen-limited systems the pathway ley → animal → manure results in substantial inevitable N-losses, compared to the near-zero N-losses observed in this C&C fertilizer system (data not shown). If nitrogen is or becomes limiting in (organic) arable farming, the losses in the animal pathway should be seriously discussed.

Conclusions

Integrating leys in farming systems is an important measure when, in the near future, production levels are to be increased with more limitations on the use of agrochemicals, high costs for N-fertilizer and pressure to reduce GHG-emissions. We have shown that leys can play an important role in pure dairy/beef, mixed dairy/beef-arable, and pure arable farming systems. Although many ecosystems services are affected by leys, nutrient provision and recycling via N-fixation of legumes, and maintenance of soil quality are important drivers behind the use of leys in all three systems (Table 5). Pest and weed control is also very important for the organic arable farms (system 2 and 3), more so than for conventional and organic dairy/beef farms. The function and the ecosystem services of the ley will determine the species and variety choice and needs more research and development. Legumes should be part of all leys for their N-fixation ability but the relative importance may differ (for example more important in C&C systems compared to dairy/beef systems). Whereas grasses in monoculture or in mixture with legumes can play an important role in weed suppression, care must be taken that this does not occur at the expense of the percentage of leguminous species. Forbs in multispecies mixtures can have a positive effect on different ecosystem services (e.g. habitat for biodiversity, drought resistance and weed control). At the moment this is the subject of research in a multisite experiment in which the yield benefits of multispecies leys and their legacy effects on a follow-on crop is investigated (O'Malley *et al.*, 2023). Also, the different duration of the leys in the three systems will affect variety choice and management of establishment. For example, persistence of red clover and forb species will play a more important role on a dairy/beef farm than on an arable farm, but early establishment by variety choice or management will be more important on arable farms. The percentage of leys in a system will depend on legislation, balance with food production, N-balance, labour balance, return to labour, etcetera, but will be about 17-40% of the total farms area. This requires customization and adaptation of the different systems over time.

Table 5. Overview of the use of leys in three farming systems; pure dairy/beef, mixed dairy/beef-arable and pure arable.

Farming system	**Pure dairy/beef**	**Mixed dairy/beef-arable**	**Pure arable**
Following crop	Fodder crop, Arable	Arable	Arable
Ley product	Forage	Forage or biomass	Cut & carry fertilizer
Ley product on or off farm	On farm	Off farm	On farm
Ley species[1]	Grasses, legumes, forbs	Grasses, legumes, forbs?	Legumes, grasses?, forbs?
Ley duration	2-3 years	1-2 years	1-2 years
Percentage of leys in system[2]	20-40%	25-33%	17-25%

[1] ?=For future research.

[2] Estimation based on case studies, the depends on a lot of factors and can change over time.

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