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Eco-efficiency of leys—The trigger for sustainable integrated crop-dairy farming systems

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Abstract

The specialisation of agricultural systems in Western Europe and the intensification of livestock and cropping production are intrinsically linked to substantial resource inputs. This intensified approach frequently leads to nutrient surpluses and biodiversity loss, resulting in detrimental environmental impacts. A transformative agricultural shift is imperative in light of climate and environmental protection objectives. Addressing this need, the Lindhof eco-efficient pasture-based milk production initiative, initiated in 2016, is a tangible manifestation of a productive and profitable dairy system integrated within a ley-based Integrated Crop-Livestock System (ICLS). Operational at the organically managed Lindhof farm, this approach involves a rotational stocking system of spring-calving Jersey cows stocked on grass-clover-herb leys embedded within a cash crop rotation. The dairy cows benefit from these highly productive swards, rich in nutritive value comparable to concentrate feeding. At the same time, the cultivated crops derive advantages from the legacy effect of leys due to nutrient exchange facilitated by grazing excreta and residual crop matter. Compared to specialised systems, the ley-based ICLS emerges as an alternative dairy production paradigm that supports many ecosystem services – including minimised nutrient losses, a lower carbon footprint and positive contributions to agro-biodiversity. These outcomes are realised without compromising overall land-use efficiency while reducing environmental and social costs of 20–30 Eurocent per kg of milk produced compared to specialised systems. Thus, the ley-based ICLS conforms to the principles of ecological intensification, enhancing functional diversity within the agricultural landscape. Essentially, the Lindhof initiative represents a holistic and environmentally responsible approach to farming that could contribute to realising the EU Farm to Fork Strategy.

KEYWORDS
eco-efficiency, grass-clover, grazing, integrated crop-livestock systems, rotational stocking

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1 | BACKGROUND

The concept of Sustainable Intensification (SI) in agriculture emerged as a proposed solution for navigating the complicated network of competing food system priorities while adhering to the defined planetary boundaries for agricultural production (Garnett & Godfray, 2012). This concept emphasises the imperative to enhance food production on existing agricultural land without further interfering with the natural ecosystem. Nevertheless, there has been a recent misinterpretation of the concept, leading to a global increase in agricultural production intensity and resource utilization. This trend has culminated in over 80% of the world's arable lands being allocated to monocultures for grain production, resulting in a decreasing crop diversity per unit of land (Altier et al., 2015). This phenomenon is also attributed to the growing expansion and intensification of the livestock sector in various regions (Godfray et al., 2010), leading to shifts in land use and a decline in agro-diversity within landscapes.

In high-income nations, specialised dairy farms are characteristic of the livestock sector, where highly productive dairy breeds are housed indoors year-round. Commonly seen in intensively managed farms in the US and central Europe, the animals are fed energy- and protein-rich diets, relying mainly on maize and imported concentrate feed (EC, 2021) to maximise milk performance per cow, while the share of grass products in these diets drops down to levels lower than 30% in terms of total energy demand. While this approach has elevated crop productivity, milk production and the dairy industry's efficiency and profitability, it has also introduced challenges such as nutrient accumulation and leaching, as well as surplus manure accumulation, reduction in drinking water and air quality, biodiversity and climate stability (Taube et al., 2014). Decoupling crop and livestock farming has resulted in a high N surplus and social cost. In northern Germany, for instance, about 75% of the surplus N resulting from N application (+100 kg N ha^{-1}) is directly linked to animal husbandry, inducing an estimated social cost of nearly 1000 € ha^{-1} (Table 1). In some regions, former grasslands have been repurposed for cultivating cereal crops and silage maize for ruminant feeding, sparking competition between arable land for animal feed and direct human food production (Karlsson & Röös, 2019).

TABLE 1 The fate of applied N and associated social costs in intensively managed northern German agricultural areas, calculated from different sources.

N-surplus (kg N ha^{-1})	+100	€ per kg N
N-losses via leaching (NO_3; NH_4; DON)	−37	13 (5–24)
N-losses via ammonia volatilisation (NH_3)	−30	14 (4–30)
N-losses via N_2O and NOx	−8	11 (6–18)
N-losses via denitrification to N_2	−20	
N-sequestration in soils (net)	−5	
Balance	0	989 € /ha (353–1932)

Note: Figures in parenthesis show site-to-site variation. Social N costs of environmental pollution (average and range) were calculated according to Brink and van Grinsven (2011). The fate of applied N (*Source*: Taube, 2016).

Consequently, an urgent need is to introduce innovative paradigms that embrace solutions advantageous to farmers, the environment and society—an actual win-win-win scenario. A shift should occur in the EU towards multi-functional grass-based dairy farming to produce milk and better protect the drinking water quality, contribute to climate change mitigation, enhance biodiversity, improve animal welfare, and create attractive landscapes. Thus, dairy farms should provide essential ecosystem services (ES) beyond milk production. However, the challenge is to integrate these economic and ecological benefits into a farming system.

2 | ECOLOGICAL INTENSIFICATION

The concept of Ecological Intensification (EI), as introduced by (Tittonell 2014), aims to improve ES and strengthen biodiversity within agricultural frameworks. Relatedly, ecological efficiency encompasses the adeptness with which ecosystems convert inputs (like sunlight, water and nutrients) into valuable outputs (such as biomass, food and diverse ES). In agriculture, attaining ecological efficiency involves realising elevated productivity with restrained resource inputs while mitigating adverse environmental repercussions. With this, agricultural systems curtail their environmental impact by optimising ecological efficiency while fulfilling the imperative for sustenance and goods. These concepts synergize closely with the principles of resource-use efficiency and waste reduction. Achieving high eco-efficiency necessitates strategic adjustments in managing individual crop and livestock operations or the broader land-use paradigm, as underscored by

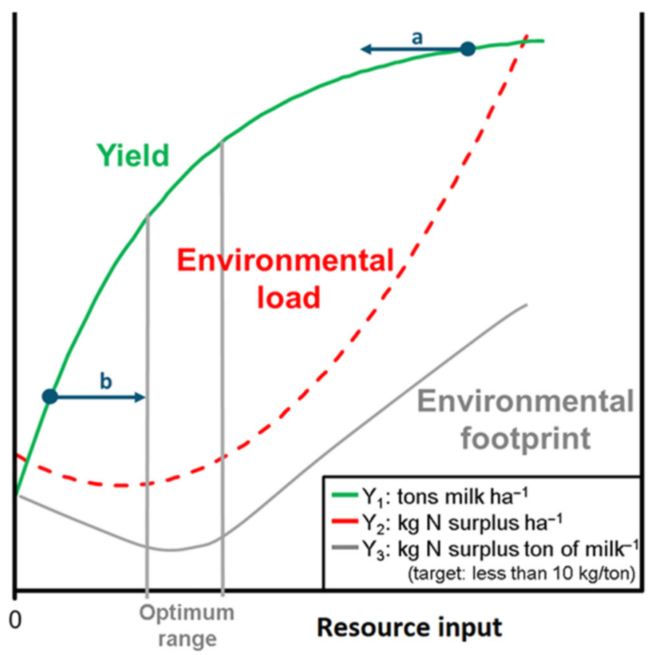

FIGURE 1 The principle of eco-efficiency illustrated by the relationship between resource input (e.g., N input [x]) and productivity (e.g., milk production [y_1]), environmental load (e.g., N surplus per ha [y_2]) and environmental footprint (e.g., N surplus per unit milk produced [y_3]).

(Wilkins, 2008). This might encompass judicious manipulation of input factors to fine-tune the equilibrium between economic outcomes (products, services, activities) and the environmental consequences embedded in production, consumption and disposal cycles.

The core principle of achieving high eco-efficiency is illustrated in Figure 1, demonstrating that as resource inputs increase, the output level typically exhibits diminishing marginal productivity; however, environmental load escalates disproportionately. The pinnacle of eco-efficiency lies where the quotient of ecological load and productivity is minimised, necessitating the acceptance of slightly reduced production levels (de-intensification) for agricultural commodities when necessary. Accordingly, to ensure overall high eco-efficiency, high-input farming systems (Point ‘a’ in Figure 1), characterised by substantial environmental load, should consider de-intensifying agricultural commodity production to enhance ecosystem service provision (ecological intensification). This involves a nuanced approach, which does not necessarily entail a complete shift to organic practices but rather a combination of strategies, so-called ‘hybrid agriculture’ strategies (Taube, 2022), to maintain a high level of land use efficiency (LUE) and to avoid leakage effects (Lambin and Meyfroidt, 2011). For example, optimising eco-efficiency might involve relocating the production of specific agricultural commodities to regions with the highest ecological efficiencies. Conversely, in regions where farms (for example, smallholder farms) are positioned at a lower point on the production function (Point ‘b’; Figure 1), characterised by low productivity, efficiency and environmental load due to minimal inputs, a strategy of sustainable intensification is required to boost food production and land use efficiency (LUE) without compromising ES (Brandt et al., 2020).

A prerequisite for high eco-efficiency in agricultural systems is circularity. The circularity concept posits the strategic harnessing of the potential of animal-sourced foods within the global food paradigm, capitalising on the intrinsic trade-offs embedded within the food system and explicitly mitigating feed-food competition. A perspective gaining traction suggests that the presence of livestock in future food systems should be contingent upon minimal feed-food competition (Mottet et al., 2017; Springmann et al., 2018; van Zanten et al., 2018). With this, livestock emerges as a transformative agent if it can convert otherwise disregarded by-products—resources that remain unconsumed or undesirable for human consumption, such as crop residues, co-products, and food chain waste—into valuable commodities like meat, milk, eggs and manure, while simultaneously rendering various ES. A study by van Zanten et al. (2018) illuminates the potential of livestock in recycling these remnants and harnessing existing grassland resources for animal production. According to these authors, such ‘low-cost livestock’ could meet an optimum of 14%–23% of the daily per capita protein demand derived from animal-sourced foods (ASF), while current figures in Europe indicate a two to three times overconsumption of protein from ASF. This strategic approach presents an effective and efficient avenue for leveraging arable land for food production. Such a trajectory is projected to curtail nitrogen (N) and phosphorus (P) losses by 40% and 46%, respectively, and greenhouse gas (GHG) emissions by 19%–50%, vis-à-vis a business-as-usual scenario (Röös et al., 2017).

In a concerted effort to tackle the challenges mentioned earlier, which are explicitly linked to animal agriculture, the European Union (EU) has embraced the ‘Farm to Fork’ strategy to address multifaceted issues within European agriculture (EC, 2020). This strategy, underpinned by agricultural circularity principles, envisions a future where livestock's role is carefully calibrated to minimise feed-food competition, leveraging their unique ability to transform discarded resources into valuable sustenance and services. In the ongoing discourse, therefore, the efficacy of ruminant livestock production in converting leftovers into animal-derived sustenance comes to the fore, albeit with relatively greater associated GHG emissions than their non-ruminant counterparts. Nevertheless, the latter escalates the challenge of feed-food competition on agricultural land (van Selm et al., 2022).

3 | A CASE FOR LEYS IN CROPPING SYSTEMS

Acknowledging that “low-cost livestock’ could play a beneficial role in future food systems, the need to implement ecological intensification and agricultural circularity concepts for diverse ecosystem benefits through a careful localization of a context of sustainable practices comes to the fore. One possibility to reduce the high environmental loads associated with the highly specialised farming practices of our modern production system (separated arable crops and dairy/pig farms) is to promote cooperation by developing joint crop rotations to facilitate nutrient cycling. Accordingly, a concrete illustration of translating the principles of ecological intensification into practice emerges through the implementation of integrated crop-livestock systems (ICLS) that includes leys. This cooperation could achieve the highest LUE and ensure social acceptance of low-level ASF in Europe when forage for dairy cows, for instance, comes from absolute grasslands (but not from peat soils due to high GHG emissions) and/or from arable land if dairy inclusion makes arable cropping systems better in terms of soil fertility and additional ES. ICLSs maximise the interaction between system components, that is, soils, plants, and animals, and, therefore, have the potential to decrease environmental impacts while maintaining production levels (Ryschawy et al., 2017). Such systems were essential in recycling nutrients in the past, but the advent of synthetic fertilisers has made them less critical (Schut et al., 2021).

The role of leys in integrated crop-livestock systems and their positive impact on the livestock of South Australia and Mediterranean states of Africa pre-and post-World War II eras, respectively, have been well chronicled by Byerlee (2023). In their review, Taube et al. (2014) expounded on the positive effect permanent grassland-based dairy farming could have on the ecological footprint of milk in our world today. Production grasslands, consisting of permanent and temporary grasslands, provide feed for herbivores and ruminants but can offer additional benefits. Perennial grasses have a more extended growing season, a dense, fibrous root system, and substantially larger below-ground biomass productivity than annual cash crops (Loges et al., 2018). Where grass-legume leys are a component of the crop rotation within the context of ICLS, nitrogen fertiliser and plant protection inputs can be lowered while additional carbon is sequestered in the soil (Goudriaan, 1992). Moreover, mixed grass-clover ley-arable systems (temporary grass of 2–5 years) can capture the benefits of grass swards temporally in combination with periods of intensive cropping and ensure greater protein self-sufficiency of the livestock farm (Peyraud et al., 2014). The termination of grasslands results in a large quantity of mineral N available to subsequent crops, thus reducing N fertiliser requirements in the arable phase of the rotation with greater yields of the following arable crop (Alderkamp et al., 2022; Lemaire et al., 2015), thus minimising nutrient leaching. Accordingly, ley systems potentially yield positive pre-cropping effects, adding biologically fixed N when legumes are included, thus reducing external N input and pesticide use (Martin et al., 2020).

The use of mixed grass-clover ley-arable systems within ICLS arrangements could improve the eco-efficiency of agricultural systems. Ley-crop rotations can provide indirect ES, such as improving soil fertility, controlling weed and pest populations, and saving energy due to the economy of avoiding tillage and fertiliser applications (Lemaire et al., 2014). Multispecies swards in leys, including tannin-rich species, may have additional benefits like reducing N_2O emission from soils via biological nitrification inhibition (de Klein et al., 2019) and mitigating enteric methane emissions when fed to livestock (Beauchemin et al., 2020). Multispecies leys could conserve and improve biodiversity by supporting various insect species (Badenhausser et al., 2009; Beye et al., 2022), thus contributing to the food chain for birds and other species (Lemaire et al., 2015). Compared to continuous arable cropping, leys improve soil structure through several biological processes, including more significant litter inputs, as well as high C and N returns from grazing animals, supplying constant food or C to soil organisms (Yeates et al., 1998). The reduced tillage disturbance characteristic of leys promotes a larger population of earthworms (Yeates et al., 1998) and herbivorous nematodes (Bouwman & Arts, 2000).

4 | ECO-EFFICIENT PASTURE-BASED MILK PRODUCTION AT LINDHOF EXPERIMENTAL FARM

The Lindhof research farm of Kiel University is an ICLS designed to demonstrate the high eco-efficiency of pasture-based milk production, where at least 75% of milk came from grassland of multispecies forage mixtures (of functional diversity). The system promotes homegrown protein provision, ensures yield stability and maintains high nutritive value. In addition, the arrangement was aimed to provide multiple ES (clean water, climate change mitigation, biodiversity, animal welfare and attractive landscapes) while maximising milk production per hectare. It was hypothesised that combining N self-sufficient high-yielding grass-clover leys with low N_2O emissions and significant carbon sequestration, along with the benefits of low input pasture-based milk production, would lead to high LUE and low environmental footprints per kg of energy-corrected milk (ECM) (product carbon footprint [PCF] and product nitrogen footprint [PNF]). Moreover, it could provide additional benefits for biodiversity and significantly reduce the social costs per kg of ECM produced. The study aimed to provide compelling data to inform policy transitions of EU agriculture towards ICLS, creating farming schemes that maximise milk yield from grass with low concentrate supplementation in a mixed farming setting based on leys (here, organic farming). The research methods adopted at the farm comprised assessing the nutritive value and forage accumulation rate, optimising pasture management, partitioning C, measuring N fluxes and enteric methane and modelling.

4.1 | The Lindhof farm

The Lindhof research farm is situated in Schleswig-Holstein by the Eckernförde Bay of the Baltic Sea, with coordinates N 54°27 E 9°57. The area experiences an average air temperature of 8.7°C and an annual precipitation of 785 mm. A spring-calving Jersey herd was managed in a 'low-input system,' stocked on grass-clover leys (2–3 years of ley phase followed by 3 years of cash crops). The dairy herd was initiated in the autumn of 2015 with 80 sensor-equipped Jersey cows, which was later increased to 100 lactating dairy cows by 2022. Breeding was done by artificial insemination using sexed semen. Milk production at Lindhof adheres to the standards set by German Organic Farming Association (Bioland and Naturland).

To achieve maximum utilization of the grass-clover leys, cows at Lindhof are strategically timed to calve between mid-January and March, aligning with the goal of optimising pasture utilization. The stocking period typically begins in March and spans 260 days, with 155 days dedicated to full-day stocking. Pastures provide over 90% of the cows' energy needs starting from the 60th day of lactation. During the initial 60 days of lactation, cows are supplemented with some concentrates and high-energy grass-clover silage. Stocking management is distinguished by an intensive rotational stocking strategy, wherein livestock receives precise daily allocations through a methodical strip grazing routine. This rigorous approach is consistently implemented from mid-April to late July, ensuring the optimal utilization of available resources and promoting both the ecological sustainability and productivity of the grazing area. The pastures are highly productive grass-clover-herb mixtures, grazed at the 3-leaf stage of perennial ryegrass, achieving energy concentrations of 7.6–7.8 MJ NEL kg^{-1} DM (NEL = Net Energy for Lactation) in May/June, with an average of >7 MJ NEL kg^{-1} DM over the stocking season. The silage cuts (baled silage) reach energy concentrations of around 7 MJ NEL kg^{-1} DM with high usable crude protein values of 183 g kg^{-1} DM in June. Herbage allocation is based on weekly sward height measurements with a GPS-based rising plate metre. These measurements are then analysed with simulation models (Peters et al., 2022) and a mobile application, all aimed at optimising daily herbage provision in terms of quantity and nutritive value.

The animals graze paddocks approximately 8–10 times yearly. Each paddock is cut for silage bale harvesting at least once during the stocking season. Starting from September, the diminishing growth rate of grass-clover in the latter half of the stocking season is counteracted by expanding the paddock. This is achieved through cover crop swards (annual ryegrass) and grass-clover swards established annually by undersowing into winter cereals. This approach ensures a consistent supply of herbage throughout the stocking season. As the third winter concludes, the animals are made to graze paddocks in February/March before fields are prepared for oat cultivation, followed by two additional cash crops. Subsequently, a new ley is established using the same method as described above.

4.2 | Productivity and production costs

A comparison between the Lindhof system and some 350 very best (in terms of profitability) typical conventional indoor dairy farms, out of more than 4000 dairy farms in the state of Schleswig-Holstein organised in an official extension service (Table 2), highlights the remarkable productivity and profitability achieved by combining a spring-calving Jersey-based herd with an intensive pasture-based approach. The Lindhof system is superior in milk production per kg of body weight, in milk composition, the proportion of milk produced from forage, a low need for purchased concentrate feed and a low adjusted reproduction rate (replenishment without stock changes). The low rearing costs reflect the comparatively low age at first calving.

The amount of milk produced from forage at Lindhof (5284 kg ECM cow^{-1}, Table 2) is based on calculations used by the advisory company *Vereinigung für Rinderspezialberatung* (VRS) e.V. According to this calculation, each kilogram of concentrate feed produces a net milk yield of more than 2 kg in energy-corrected milk (ECM). This implies

TABLE 2 Production parameters, economic results and nitrogen balance (2019/20) of the experimental farm Lindhof from Kiel University compared to the average of 356 dairy farms fully evaluated by *Vereinigung für Rinderspezialberatung* (VRS), a chamber of agriculture (extension service) in Schleswig-Holstein, Germany.

	Unit	Lindhof	Average of 356 by VRS
Dairy herd	Number of cows	94	166
Body weight	kg cow^{-1}	470	670[a]
Milk yield	kg ECM cow^{-1}	7007	9433
Milk yield natural	kg cow^{-1}	5728	9257
Milk yield per kg body weight	kg ECM kg^{-1} BW	14.90	14.08
Milk solids production (fat plus protein)	kg cow^{-1}	592	702
Fat	%	5.59	4.20
Protein	%	3.99	3.45
Concentrate feeding	dt cow^{-1} year^{-1}	8.00	28.10
Concentrate feeding efficiency	g kg^{-1} ECM	120	295
Milk production per ha MFA on farm[b]	kg ECM ha^{-1} MFA	10,946	14,866
Milk produced from forage[c]	kg ECM cow^{-1}	5284	3767
Proportion of milk produced from forage[c]	%	75.4	39.9
Adjusted reproduction rate	%	18.2	33.4
First calving age (LKV-SH, 2021)	Months	24.6	28.4[e]
Calving interval (LKV-SH, 2021)	Days	362	400[e]
Costs for veterinary, medicines + hoof care	ct kg^{-1} ECM	1.48	1.64
Total feed costs[d]	ct kg^{-1} ECM	16.81	22.12
Costs of producing forage	ct kg^{-1} ECM	12.17	13.35
Concentrated feed costs	ct kg^{-1} ECM	3.83[g]	8.77
Labour cost	ct kg^{-1} ECM	11.02	10.25
Mineral N fertiliser input	kg N ha^{-1} MFA	0	99
N balance[f]	kg N ha^{-1} MFA	88	149

Abbreviations: ECM, energy-corrected milk; MFA, main forage area; SH, Schleswig-Holstein.
[a]Estimated value based on the average of the breeds.
[b]Without area requirements for imported feed.
[c]Milk from concentrates excluded according to LK-SH (2020) calculation.
[d]Rearing replacement heifers included.
[e]Farms in the same region.
[f]Farm-gate N balance of only the dairy operation.
[g]From organic production at a 63% higher price.

that the energy required to maintain the cows is predominantly met by forage. However, if the energy demand for maintenance is distributed evenly over the total energy consumed by the animal (as the sum of forage and concentrated feed), which is more realistic, the calculated milk produced from forage at Lindhof would increase to 5865 kg ECM cow^{-1} and the 'real' milk gain from concentrates is close to 1 kg ECM per kg of concentrate feeding and thus halved. Applying this revised method to the data from the typical conventional indoor dairy farms in the state (as shown in Table 2) results in an elevated estimate of milk produced from forage, rising from 3767 to 5519 kg ECM cow^{-1}. This demonstrates that in both systems, the contribution of milk from forage is underestimated, while milk from concentrates is overestimated. These findings have noteworthy implications for calculating feed costs: the actual prices of concentrate feed per kilogram of ECM are significantly greater than those reported by VRS.

Examining the energy sources for the dairy cows in the Lindhof system reveals that approximately 48% of their total annual energy intake comes from grazed pasture, followed by 35% from grass silage and 16% from concentrates. When evaluated regarding the consumed crude protein, around 47% of the milk is attributed to grazed pastures, 41% to protein-rich grass silage and only 11% to grain-based concentrates. This breakdown underscores the substantial role of pastures and silage in the overall milk production process within the Lindhof system. Meanwhile, Lindhof Farm achieved remarkable cost savings in forage production during the 2019/20 accounting year, which is representative of the long-term average. The full cost of forage production based on grass-clover managed in a mixed harvesting system of mowing and grazing was, in the farm accounting year 2019/20, 16.47 cents per 10 MJ NEL and 0.74 cents per kg of crude protein. This significantly undercuts the expenses of similar farms, as shown in Table 3. Other factors contributing to the lower cost of production include the annual cost of veterinary care and hoof maintenance per cow, which was 11% lower for Lindhof than for comparative farms. Also, the age at first calving of 24.6 months and a calving interval of 362 days demonstrates the positive economic effect of good fertility management.

One other critical factor influencing production economics is labour costs. Contrary to the conventional belief that pasture management escalates labour demands, Lindhof Farm has proven otherwise. At the Lindhof farm, extensive documentation enables the allocation of working hours to the individual branches of the business, maintaining a low requirement of working hours per cow annually. This is remarkable as the economy of scales argues towards the double-sized herds of the indoor control group. The farm's well-designed infrastructure facilitates this achievement, ensuring easy access to all pastures from the milking parlour. Moreover, Lindhof enjoys substantial savings in manure handling costs compared to indoor farms. Lindhof Farm's innovative practices in forage production, livestock management, and labour efficiency have yielded cost advantages and challenged preconceived notions about pasture-based milk production. Their comprehensive approach, supported by strategic infrastructure, highlights the potential for sustainable and economically viable food production.

4.3 | Ecological metrics

4.3.1 | Nitrate leaching

Dairy production significantly contributes to the pollution of surface and groundwater with nitrate (NO_3). This mounting concern has spurred the implementation of various regulations, including the European Union Nitrate Directive. The findings from 3 years of field measurements at Lindhof (Smit et al., 2021) offer valuable insights into nitrate leaching across different grassland systems. The outcomes reveal that fertilised permanent grasslands and grazed grass-clover swards exhibited relatively low (<10 kg N ha^{-1}) and medium (10–28 kg N ha^{-1}) levels of nitrate leaching, respectively (Figure 2). As anticipated, grazing led to greater NO_3—N losses than cutting. Within grazed leys, the extent of leaching losses grew with the age of the swards. On average, significant differences between permanent grasslands and leys were not observed. The relatively modest nitrogen losses from grazed swards at Lindhof can be attributed to two factors: (i) diminished sward clover proportion in grazed versus cut swards, and (ii) the extraction of nitrogen through at least one summer silage cut, even from all grazed paddocks.

In the above study, NO_3—N leaching was contingent on the availability of mineral nitrogen, land usage, soil type, prevalent weather conditions, and the duration of the growing period. The mean cumulative nitrate leachate over the experimental period was 8.5 ± 1.8 kg NO_3—N ha^{-1}. Cover crops under grazing and fertilisation exhibited the most substantial N-leaching losses (~20 kg NO_3—N ha^{-1}). However, the values documented at Lindhof fell below those reported in the literature range (10–80 kg NO_3—N ha^{-1}; Biernat et al., 2020; Eriksen et al., 2015; Askegaard et al., 2011), positioning Lindhof at the

TABLE 3 Full costs analysis of forages in the 2019/2020 financial year.

	Lindhof grass-clover-silage	VRS 2019/20[a] grass-silage	VRS 2019/20[a] maize-silage
Energy yield, MJ NEL ha^{-1}	57,228	57,593[a]	84,746[a]
Crude protein yield, kg CP ha^{-1}	1, 275	1, 456	907
Total costs, € ha^{-1}	943.75	1865.98[a]	2039.44[a]
Total cost, ct 10 MJ^{-1} NEL	16.47	32.40[a]	24.07[a]
Total cost, ct kg^{-1} CP	0.74	1.28	2.25

[a]All including land cost; VRS, *Vereinigung für Rinderspezialberatung*, a chamber of agriculture (extension service) in Schleswig-Holstein, Germany *Source*: LK-SH, (2020).

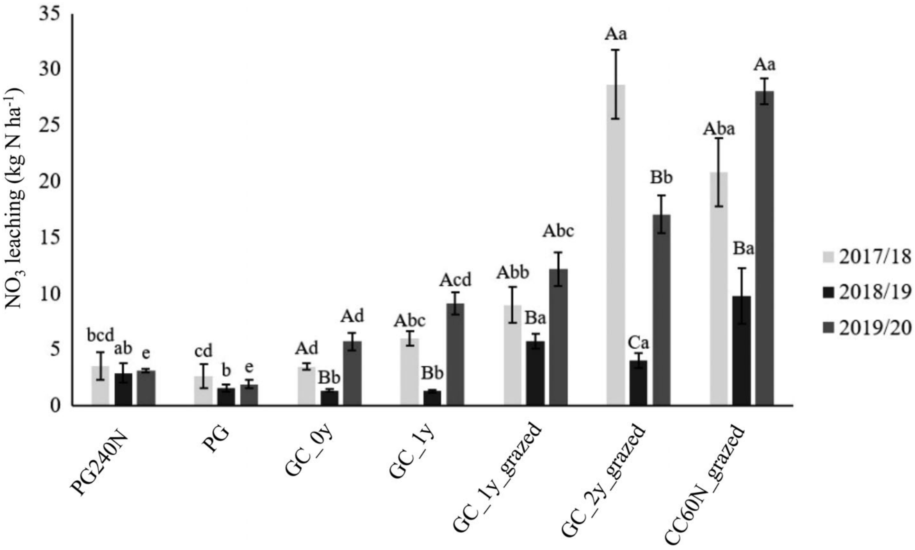

FIGURE 2 Average nitrate leaching losses (kg NO_3—N ha^{-1}) of the different systems (permanent grassland (PG with no fertilisation), PG240N is PG receiving 240 kg N ha yr^{-1}; GC (with no fertilisation) is grass-clover swards; 0, 1, 2 years old; CC60N is catch crop fertilised with 60 kg slurry N ha^{-1}); Permanent Grassland (PG), Grass clover (GC), cover crop (CC) (annual ryegrass); (Smit et al., 2021). N load of 30 kg N ha^{-1} is equivalent to the threshold exceeding 50 ppm nitrate concentration in the leachate (275 mm of percolated water)–EU limit in drinking water is 50 ppm.

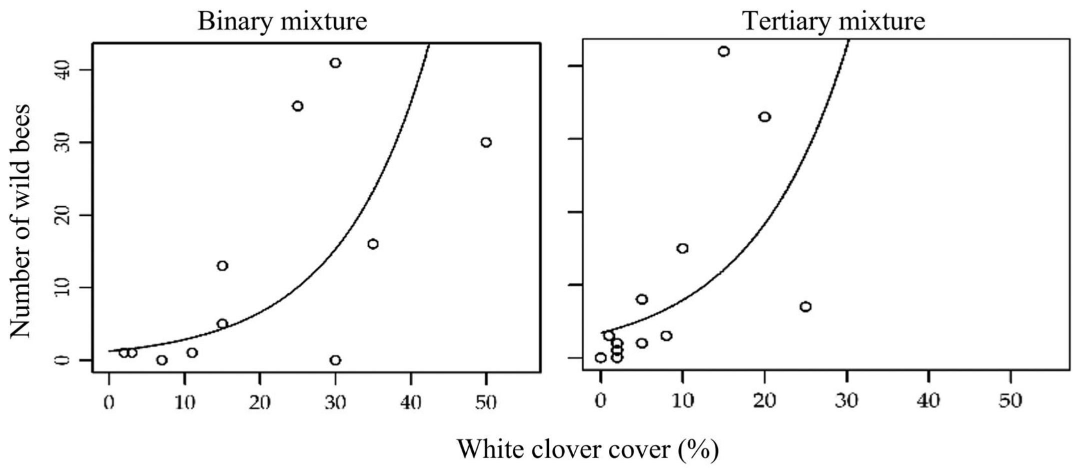

FIGURE 3 Effect of white clover cover on wild bee abundance in grazed grass-clover swards (binary mixture of perennial ryegrass and white clover; a tertiary mixture of perennial ryegrass, white clover and red clover) (Beye et al., 2022).

lower spectrum under comparable environmental conditions. Overall, the examined treatments consistently maintained nitrate concentrations well below 25 ppm, thus promoting a dilution effect within the crop rotations. This might be due to a highly effective rooting system, with root length density exceeding 100 km per m^2 per year measured on grasslands at Lindhof (Chen et al., 2016). Moreover, a pronounced N carry-over effect was observed from grass-clover swards to the ensuing cash crop unit (Smit et al., 2021), consequently diminishing the risk of groundwater contamination stemming from grazed leys. This carry-over effect also led to a decreased nitrogen fertiliser requirement for the subsequent crop following the grazing of the leys.

4.3.2 | Biodiversity

Flower-visiting insects have an essential function in plant pollination, and pollination by bumblebees, for instance, increases the yield of many crops (Orford, 2016). Regrettably, pollinator populations are facing a decline, raising concerns (Bommarco et al., 2012). A study conducted at Lindhof (Beye et al., 2022) shows the potential of legume mixtures, particularly those incorporating *Trifolium* spp., in augmenting bumblebee abundance. Among the diverse mixtures explored, a noticeable effect was observed in the grazed binary and tertiary mixtures of grass-clover leys (consisting of perennial ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.). The study underscores that augmenting species richness and incorporating legumes in grass-clover leys promotes agro-biodiversity compared to conventionally managed grasslands without flowering legumes. Clover incorporation in the grassland (between 20 and 40%) elevated wild bee abundance (Figure 3).

The study recorded a remarkable count of 541 wild bees, encompassing bumblebees and a solitary bee species, spanning two genera and 10 species within plant-species-enriched grass-clover swards. In contrast, no wild bees were observed within nearby conventionally managed grasslands for silage production (with 4–5 cuts annually). Nevertheless, the potential of these species-enriched mixtures to strengthen wild bee populations faced limitations under intensive stocking. Notably, areas excluded from stocking harboured a greater number of long-tongued bumblebees in binary mixtures (*Lolium perenne* and *Trifolium repens*) and multispecies mixtures (*L. perenne*, *T. repens*, *T. pratense*; *Lotus corniculatus*, *Cichorium intybus*, *Plantago lanceolata*, *Carum carvi*, *and Sanguisorba minor*) than grazed areas. Although the outcomes of this study displayed modest results, the authors indicated that by introducing a more diverse range of forage species with open flowers across successive phenological phases and adjusting stocking practices accordingly, a continuous and varied floral resource for insects could be established.

4.3.3 | Greenhouse gas emissions

In an experiment at Lindhof, adding herbs to the grass-clover swards did not provide additional benefits in terms of enteric methane reduction (Loza et al., 2021), nitrification and denitrification losses (Nyameasem et al., 2021) or forage accumulation (Lorenz et al., 2020) as the herbs were maintained at low-yield proportions throughout the stocking season. Nevertheless, enteric methane emissions per unit of milk were remarkably low (averaging 8.8 g CH_4 kg ECM^{-1} and 9.8 g CH_4 cow^{-1} day^{-1} for spring and summer measurements, respectively) compared with literature values (Figure 4). Notably, these values stood significantly lower than the previously documented 17.9 and 17.4 g CH_4 kg ECM^{-1} for Jersey cows fed 0 and 4 kg of concentrate, respectively (van Wyngaard et al., 2018), as well as the 13.4 g CH_4 kg ECM^{-1} reported for Jersey cows fed 61% concentrate (Olijhoek et al., 2018). The lower CH_4 emissions and enhanced milk output were attributed to the superior quality of the feed (Loza et al., 2021).

In a related study at Lindhof, Nyameasem et al. (2021) observed that the greatest emission factor for N_2O—N (stemming from cow urine and dung) was less than half of the IPCC default value (0.30% compared to 0.77%). The capacity of the pastures to effectively harness nitrogen inputs from excreta patches was linked to their heightened nitrogen uptake ability. Although differences were not statistically significant ($p > .05$), there was a notable trend of increasing pasture diversity associating with decreasing N_2O emission intensity in the above study. Also, the long-term use of grass-clover in crop rotations was found to accumulate soil carbon substantially (De Los Rios et al., 2022; Reinsch et al., 2018), which significantly reduced the PCF of milk production at Lindhof. The PCF linked to milk from the Lindhof grazing system stands at approximately 0.6 kg CO_2eq kg^{-1} ECM, in stark contrast to the more than 1 kg CO_2eq kg^{-1} ECM attributed to conventional milk from year-round indoor systems (Figure 5).

Although the additional benefits offered by the ley system are yet to be translated into monetary terms, it is anticipated that with milk yields ranging from 750 to 900 Mg ECM per farm annually and a projected CO_2 price of 100 € t^{-1} of milk set for 2030 (Statista, 2023), the advantageous position of the grazing system in terms of mitigated greenhouse gas emissions amounts to around 5 cents kg ECM^{-1}, while also maintaining comparable LUE. In their study, Reinsch et al. (2021) underscored the challenges faced by dairy-focused farm systems in achieving farm nitrogen (N) surpluses below 100 kg N ha^{-1} (refer to Figure 5). A clear relationship between N balance and GHG emissions showed that the farms with greater N surpluses also had greater GHG emissions per unit of milk and unit area. A decrease from an average farm N balance of +150 kg N ha^{-1} down to about +50 kg N ha^{-1}, as realised in the Lindhof system, would result in a substantial mitigation potential for social costs caused by lower environmental N pollution. We estimated the avoided environmental costs (Table 4; ct kg^{-1} ECM) using available prices from the literature to provide a rough estimate

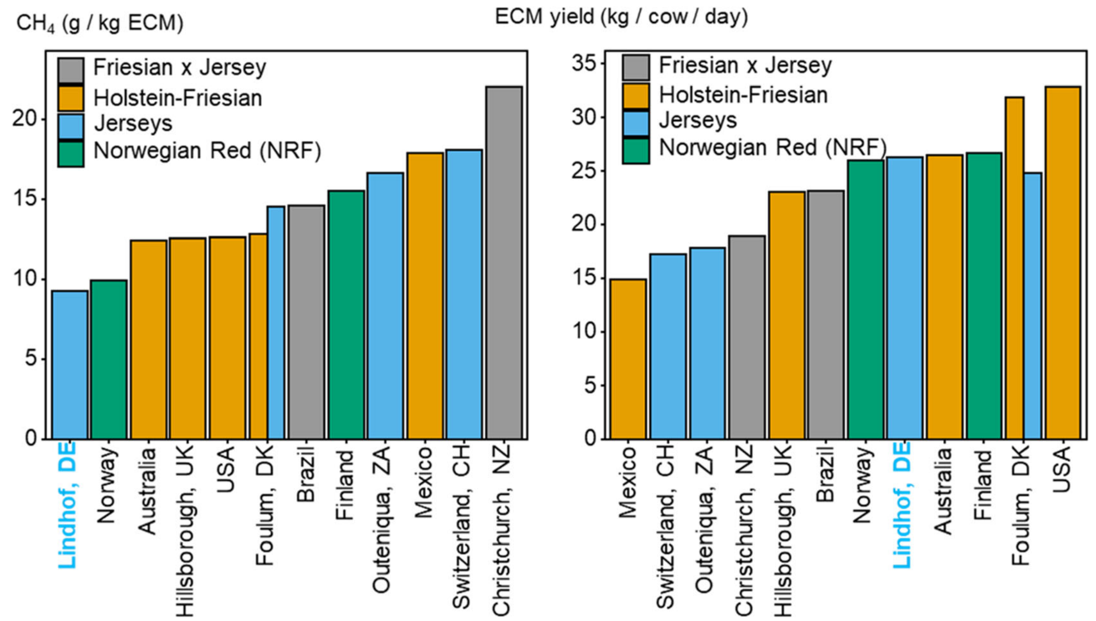

FIGURE 4 Enteric methane emission and milk production from Jersey cows at Lindhof compared with literature values. *Source*: Loza et al. (2021).

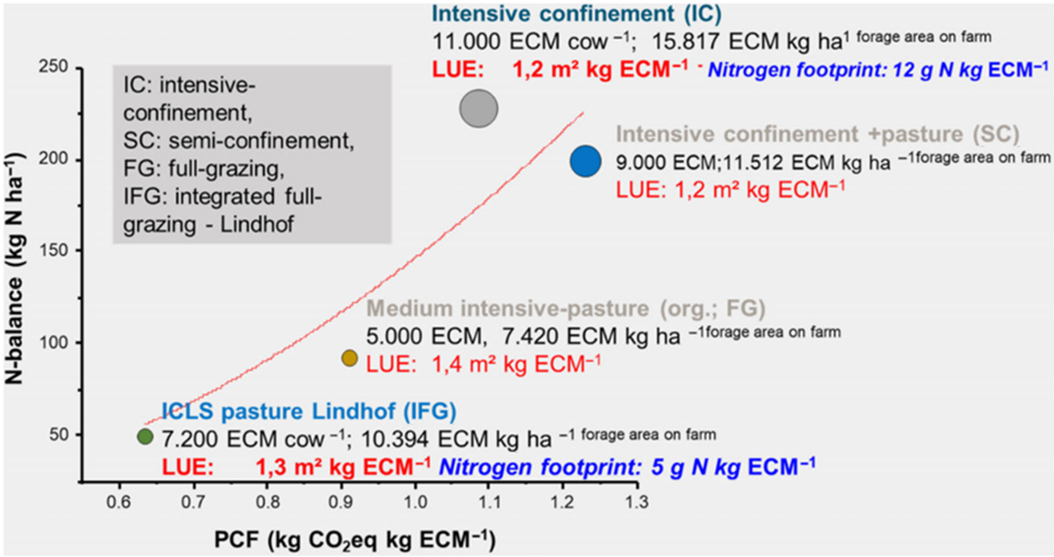

FIGURE 5 Relationship between Farm N balance and greenhouse gas (GHG) emissions per ha (left) and Product Carbon Footprint (PCF) and Product Nitrogen Footprint given as N surplus per kg ECM (PNF) (right) among the different systems (FG, full-grazing; IFG, integrated full-grazing; IC, intensive-confinement; SC, semi-confinement) modified according to Reinsch et al. (2021).

TABLE 4 Avoided abiotic environmental costs per kg ECM compared between the Lindhof system and intensive indoor system.

	Indoor dairy	Lindhof	Difference	Unit cost	Social cost avoided by Lindhof system (€ kg^{-1} ECM)
GHG, kg CO_2eq kg^{-1} ECM	1.10	0.60	0.50	100 € t^{-1} CO_2[a]	0.05
Surplus N, g N kg^{-1} ECM	12.00	5.00	7.00	10 € kg^{-1} N[b]	0.07
Surplus P[d], g P kg^{-1} ECM	1.20	0.01	1.10	120 € kg^{-1} P[c]	0.13
Total					0.25

Abbreviation: ECM, energy-corrected milk.
[a]Statista (2023). https://www.statista.com/statistics/1334906/average-carbon-price-projections-worldwide-by-region/.
[b]Brink and van Grinsven (2011).
[c]UBA (2021). https://www.umweltbundesamt.de/tags/phosphor.
[d]Phosphorus was calculated using data on concentrate feeding and mineral fertiliser import.

regarding social cost avoided by the Lindhof system (IFG) relative to the indoor system (IC), according to Reinsch et al. (2021). The socially spared cost attributed to adopting the Lindhof system was computed at 25 cents kg ECM^{-1}, with the most significant cost component being 13 cents kg^{-1} ECM arising from phosphorus (P) pollution. We envisage that comparable calculation methods will become more critical regarding greenhouse gases and nitrogen loads going forward.

The 2.5-year grass-clover ley phase, integral to milk production at Lindhof, yielded supplementary benefits for the downstream cash crop segment of the farm. Within the soil, nitrogen-rich grass-clover roots and stubble are stored, safeguarding them against leaching, and subsequently serve as a vital N source, furnishing nearly 150 kg N ha^{-1} to the directly succeeding crop (in this case, edible oats). The farm's manure resources were applied to the subsequent winter cereal crops, leading to heightened yields. This approach effectively ensured that the cereal crops functioned as a practical counterbalance, compensating for the excess nitrogen from milk production (approximately 88 kg N ha^{-1} of grass-clover forage; Table 2). The cumulative areas allocated to crops and pastures culminate in an N balance of +18 kg N ha^{-1}. This approach concurrently facilitates the reduction of inevitable N losses while contributing to a positive humus balance. Accordingly, ley-based milk production can be associated with a very low carbon and nitrogen footprint as well as a high LUE, contributing significantly to more functional diversity in agriculture. On the other hand, specialised all-indoor high-input/high-output milk production systems can be costly for society.

5 | CONCLUSION

Specialised dairy systems within Western Europe exhibit robust milk output per hectare, deriving considerable economic advantage. These systems possess the potential to yield substantial incomes and effectively compete within the milk market, provided social costs remain unaccounted for. This economic competition, however, depends on milk price and the extent of the competitive advantage of low feed costs generated from grazed systems. The ongoing trend of specialisation and intensification in dairy production must align with the imperative to mitigate regional-level greenhouse gas and nitrogen emissions. Currently, these systems deviate from the principles of ecological intensification. Our case study confirmed that the ongoing specialisation and the intensification of dairy production do not adhere to the need for mitigating GHG and N emissions at the regional level.

Contrastingly, the Lindhof case illustrates the advantages conferred by a grass-clover ley-based ICLS, particularly when compared to specialised systems in terms of a spectrum of ES. Even when considering equivalent producer prices observed in conventional systems, the Lindhof approach emerges as economically competitive. Remarkably, the Lindhof approach reaches these outcomes while maintaining a commendable level of LUE. As such, this system embodies a 'resilient ICLS narrative' (comprising ley systems and pasture-based dairy) that markedly enhances functional diversity within agriculture, considerably curtailing social costs, and aligns with the goals outlined in the Farm to Fork Strategy. Linking high milk production with grazing in mixed farming systems is one strategy for the economic resilience of (dairy) farming and providing long-term ES for society. However, integrating ley-based ICLS into the dairy production sector necessitates further research, development, advisory services, and political support to realise its full potential.

6 | CONSIDERATIONS FOR THE FUTURE

Enhancing the eco-efficiency of agricultural land-use systems by including ruminants as recyclers (consuming residues and products from permanent grasslands and leys) holds significant promise. This approach not only presents the potential to decrease environmental impact but also offers the advantage of remarkably low-cost food production. By capitalising on these aspects, agricultural systems can take steps towards sustainability while maintaining economic viability. Nevertheless, ecological intensification might only work under some conditions, for instance, due to crop-specific environmental constraints, reducing crop productivity. For such cases, Taube (2022) suggested the concept of hybrid agriculture, which combines ecological and conventional elements to produce optimum economic and environmental goods and services. Such a practice would require further research to establish its workings and quantify its effects. Additional specific questions arise as we consider adopting and implementing such strategies. First of all, are more stringent certification measures necessary to ensure the integrity of these practices? For instance, could a 'grass milk' certification, which requires that a substantial portion of feed protein and energy, as mentioned above, originate from grass (e.g., >75%), give consumers greater confidence in sustainability claims? Secondly, while life cycle assessment methodology offers a comprehensive view of the environmental implications of various systems, does it include the complete spectrum of benefits associated with ley systems, potentially extending beyond metrics like the carbon footprint? Could further research show the often-hidden social costs of high input and high output systems, aiding in quantifying their overall impact on society? Finally, considering policy implementation, a critical question regarding how the benefits of ley systems can be effectively integrated into the Common Agricultural Policy (CAP) arises. Could mechanisms such as a 'Public Goods bonus' (DVL, 2020) incentivise farmers to transition towards these more sustainable practices, acknowledging their positive impacts on the environment and the broader society? As we move forward in shaping the future of agriculture, these questions need further exploration and consideration.

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CONFLICT OF INTEREST STATEMENT

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author/s.

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