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Very Low Nitrogen Leaching in Grazed Ley-Arable-Systems in Northwest Europe

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Abstract: High input dairy farms that are located on sandy soils in northwest Europe are predisposed to substantial nitrate leaching during a surplus of winter precipitation. Leys within integrated crop-livestock systems play an important role in soil fertility, soil C sequestration and soil N mineralization potentials. Therefore, leys are a feasible option that can be utilized to reduce local N losses to the environment, especially following maize grown for silage. We hypothesize that grass-clover leys ensure low nitrate leaching losses even when grazed intensively. The extent to which NO_3-leaching occurred across seven different pasture management systems in terms of their sward composition, cutting, grazing, fertilization and combinations thereof was investigated in integrated animal-crop grazing systems over three winter periods (2017/2018, 2018/2019 and 2019/2020). The observed grazed systems were comprised of cut-used- and grazed grass-clover swards (0, 1 and 2 years after establishment following cereals), a catch crop grazed late in the year as well as a cut-used permanent grassland for comparison. Overall, all treatments resulted in nitrate leaching losses that did not exceed the WHO-threshold (25 mg nitrate/L). The highest level of NO_3-leaching was observed in the catch crop system and the lowest in cut-used permanent grassland, with NO_3-N losses of 19.6 ± 5.3 and 2.1 ± 0.3 kg NO_3-N ha^{-1} $year^{-1}$. Annual herbage yields were in the range of 0.9 to 12.4 t DM ha^{-1} and nitrogen yields varied between 181 ± 51 and 228 ± 66 kg N ha^{-1} during the study period. The highest herbage-N-yields were observed from the 1- and 2-year-old grass-clover leys. The highest N-field-balance was observed for the grazed leys and the lowest for the cut-used permanent grassland. However, no correlation was found between the highly positive field-N-balance and the amount of NO_3-leached. This indicates a high N carry-over from grass-clover swards to the subsequent cash crop unit instead of increasing the risk of groundwater contamination from grazed leys in integrated animal crop-systems and underlines the eco-efficiency of dairy farming based on grazed ley systems.

Keywords: leys; groundwater; rotational grazing; organic farming; multi-species swards

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1. Introduction

Dairy systems in northwest Europe strive to increase milk productivity, although the amount of forage land available remains the same. This has led to a land-use intensification in forage production and an increased level of supplementary feed imports at farm-gate, which is often associated with negative environmental effects. This makes the sustainability of confined systems, which are often used, questionable. The farm-nitrogen-balance of dairy systems increased and resulted in the N leaching to groundwater, which often reaches the critical limit of nitrate (NO_3) per litre [1]. As an example, in northern Germany, most dairy farms are located on sandy soils due to the existent land-use competition with cash-crops for fertile soils. The water retention capacity of these soils is low and the surplus of winter precipitation in these areas means that they are predisposed to substantial NO_3-leaching [2], especially when N is supplied in excess of the plant needs [3]. The majority of N leached from soils consist of NO_3, whilst NH_4 is considered to be less important.

Dairy production is therefore considered as one of the main pollutants of NO_3-N in surface- and groundwater [4,5] which presents a growing concern and an environmental problem [6,7]. This has led to the establishment of the European Union Nitrate Directive [8], the Water Framework Directive [9] and the Groundwater Directive [10] to protect both surface and ground water from NO_3 contamination as a consequence of agricultural use. This would also be in accordance with the European Nitrogen Assessment (ENA) which identifies challenges and threats associated with N pollution [11] while enhancing public awareness regarding how best to approach these challenges as mitigation options. To achieve a more sustainable balance between profitability and the environmental impact effects of dairy farming, an increased urgency exists to focus on adapting current agricultural production systems [12]. The modification of farming practices is required to support reduction strategies in solving environmental problems that are caused by currently followed agricultural practices [13]. Low-input farming systems could serve as a platform to achieve this goal, to ensure adequate production is still achieved while minimizing the negative environmental effects associated with dairy farming practices.

The inclusion of forage herbs in grass-clover swards has been found to encourage a reduction in the environmental impact of milk production [14]. Several other publications support this statement and indicate that the inclusion of legumes and forage herbs in pastures can reduce the impact of milk on the environment [6,15,16]. Forage crops in mixed farming systems, also referred to as ley-arable-systems, have traditionally been used in Europe as an additional source of feed for ruminants. Traditionally, organic farming follows the approach of combining livestock and crop production as well as incorporating a high percentage of forage legumes in the crop rotations [17–19]. Increased pressure, as a result of agricultural policies, ensured the integration of these forage crops into arable systems. Moreover, the use of legume-based forage production increases the N cycling efficiency which leads to lower N surpluses and less environmental loads of reactive N [20]. It is possible that the introduction of deep-rooting legumes such as red clover and bird's-foot trefoil (*Lotus corniculatus*), as well as forage herbs, into a mixture of perennial ryegrass could also help reduce N leaching. Another method by which to remove N from the sward is by incorporating silage cuts. The admixture of forage herbs or legumes in pastures can affect the yield performance and agronomic traits positively and can further provide environmental benefits [21].

Ruminant-based ley-arable-systems in the temperate conditions of north-west Europe are considered to be a viable strategy in achieving sustainable intensification [22]. These mixed systems, that are based on grazed leys, have multifunctional benefits including soil carbon sequestration, a prevention of runoff and soil erosion, weed suppression and a reduction in N leaching [23–25]. However, the introduction of grazing animals into farming systems increases the risk of N losses as most of the ingested N from animals is excreted back on to the swards via urine and faeces during grazing [2,14]. Urine that is deposited onto pasture can amount to as much as 200–2000 kg N ha^{-1} [26] which by far exceeds the uptake capacity of plants. If N is applied in excess of plant needs, it may increase the risk of nitrate leaching and other forms of environmental pollution [3]. Due to poor management, excess N has become more apparent on farms with high N inputs. The difference between the N input and its output in the system can amount to up to 450 kg N ha^{-1} $year^{-1}$ due to a low level of N recovery in milk and meat [27]. It has been shown that the use of diverse mixtures in pastures could reduce the N surplus in forage and, consequently, the N excretion from animals and can also reduce the extent of N leaching [28].

Perennial ryegrass (*Loliumperenne* L.) swards are commonly used for grazing in pasture-based systems. Other pastures can include a mixture of ryegrass-white clover (*Trifoliumrepens* L.) and/or red clover (*Trifoliumpratense* L.) swards. Grass leys have been adopted for grazed systems and are beneficial in reducing the environmental effects associated with grazed dairy systems. Under the temperate conditions of northern Germany, multispecies leys can be used to increase its biodiversity without compromising on the forage yield and quality [21]. Grazing systems have also been positively linked to consumer preference [29,30]. Grass-based dairy systems are therefore considered to be highly competitive [31] as well as environmentally friendly and economically viable [31,32]. However, the intensification and mismanagement of pastures can increase the rate of nutrient losses and may lead to the imbalance of nutrients in such systems [33]. Moreover, with an increase in the sward age, intensive grazing management may increase the risk of N surpluses, due to the accumulation of organic N from faeces only becoming erratically available for plant growth with increasing soil N during the weeks after excretion [34].

Catch crops are used to retain N during winter. Moreover, catch crops also have the benefit of providing additional forage. The inclusion of catch crops in ley-arable systems has indicated the role and benefits associated with these cover crops to reduce nutrient losses during winter drainage through the re-capture of N. This is the case if the N demand of catch crops does not meet the N supply from the decay of soil organic matter. Catch crops can reduce soil mineral N from the soil profile and, consequently, the risk of N leaching losses [35]. This is particularly important in agricultural systems with a low of external N supply, such as organic farming. The amount of recovered N from catch crops will depend on the quantity of N that remains in the soil, the prevailing weather conditions and the length of the growing period [36,37]. Moreover, catch crops can provide additional forage later in the year, at which point the forage yield on the farm decreases due to lower temperatures and radiation. Grazing catch crops late in the year also poses additional risks. An increased N leaching as a result of trampling patches and the N excreted from a grazing animal during this period are associated with higher levels of rainfall and wet soil conditions. For this reason, the integration of these catch crops into ley-arable systems needs to be planned and examined in existing grazing rotations to ensure their economic and environmental success.

In the current study we aimed to assess the effects of grazing in a ley-arable-system on groundwater protection. We hypothesize that the combination of highest root length density from perennial ryegrass [38] on the one hand, and the tap root system from red clover and herbs on the other hand, ensure the highest N uptake efficiency and, as a consequence, the lowest nitrate leaching figures. Thus, we evaluated the extent to which N leaching occurs under sward ages of differently grazed, diverse mixtures in the context of an on-farm research study in northern Germany. Subsequently, N leaching was measured during winter and compared with cut-used permanent grassland and cover crops cultivated after ley removal as a pre-crop. The results from the current study could provide insight into how best to reduce N leaching, which would assist in pasture management and in developing mitigation strategies to combat excess reactive N as a result of dairy farming under temperate climate conditions. Accordingly, in this paper, we present results from field trials over a three-year period. We hypothesize that grass-clover leys ensure low nitrate leaching losses even under intensively grazed conditions.

2. Materials and Methods

2.1. Experimental Site Description

An on-farm research study was conducted on temporary and permanent grassland sites at the experimental farm of Lindhof (54°27′ N, 9°57′ E, 10 m.a.s.l.) by the Grass and Forage Science group, Kiel University, Germany. The research farm is located on the Baltic Sea shoreline at the Eckernförde Bay. The area has a temperate oceanic climate with a long-term (1991–2020) mean annual temperature of 9.3 °C and long-term mean annual rainfall of 754 mm. Historically, the site was used for a five-year crop rotation for arable crops until 1993. Afterwards, it was converted to an organic farming system according to stipulations of the association "Bio-land" (which by definition prohibits the use of chemical fertilizers and pesticides) and some arable fields were converted to permanent grassland concurrently. Beyond these permanent grassland fields, the grazing system on the experimental farm could best be described as a two-year grass-clover-ley system in an organic four to five-year crop rotation (2 years of grass-clover; followed by two to three years of crops: oats/winter triticale, faba beans/winter spelt, consecutively). The grass-clover swards are established as an under-storey in the winter spelt. The total farm area is 121 ha comprising of 56 ha for herbage production, where 9 ha are permanent grassland, and 46 ha grass-clover-leys are utilized. The leys were rotationally grazed by 85 Jersey cows. The stocking rates for dairy cows on pastures were adjusted in accordance with the non-destructive aboveground biomass measurements (AGB) that were obtained with a yield-plate-meter to ensure an optimal forage allowance of 1 t DM per ha between one and two grazing days per grazing cycle. They usually have access to the pasture for an average of 292 days per year^{-1} from March to November. Swards which were outside of the range of the milking parlor were cut four times per year to make silage. The grass-clover swards did not receive any additional fertilizer N with the exception of biological nitrogen fixation (BNF). All cattle manure produced during the winter were used in cereals and for cut-used permanent grassland as well as for catch crops prior to seeding. In the ley-arable system of the experimental farm, catch crops (annual ryegrass) were established on some fields after a cereal harvest and were grazed twice between October and December. Cattle slurry application was applied with trailing hoses. The soil type on the experimental site can be classified as a loamy sand to sandy loam soil. The soil properties were likely comprised of 11% clay, 29% silt and 60% sand with a 1.7% C_{org} in the topsoil (0–30 cm) [39]. The soil bulk density was 1.53 g cm^3. The winter period is defined, in this study, as the months spanning December–February, spring as March–May, summer as June–August, autumn as September–November.

2.2. Experimental Layout and Treatments

An experiment was conducted on the farm paddocks, to investigate the NO_3-leaching losses from different sward ages of grazed leys and grazed catch crops. A cut-used permanent grassland served as the control. The different fields were randomly arranged across the experimental farm during three experimental years (2017/2018; 2018/2019 and 2019/2020). The different systems were examined, and information regarding the sward age, grazing interval and slurry fertilization was collected and has been provided in Table 1.

Table 1. Different pasture systems and fertilization levels evaluated in the current field study.

Nr	System	Sward Age (Years)	Management	Fertilization (kg N ha^{-1})	Abbreviation
1	permanent grassland	>20	4× silage cuts	0	PG
2				240	PG240N *
3	grass-clover-ley	1	5× silage cuts	0	GC 1y
4		0 ***	2× grazed	0	GC 0y
5		1	8× grazed, 1× silage cut	0	GC 1y grazed
6		2		0	GC 2y grazed
7	cover crop	0 *	2× grazed	60	CC 60N grazed **

* applied as cattle slurry in 4 dressings per year. ** applied as cattle slurry in one dressing prior to catch crop seeding. *** grass-clover under-storey following grain harvest.

2.3. NO_3-Leachate Analysis

Soil water samples were obtained using ceramic suction cups with a pore size of 1 µm, 54 mm in length and a diameter of 20 mm (Mullit, ecoTech, Bonn, Germany) over the autumn/winter period. The suction cups were installed in the soil at a depth of 75 cm at a 60-degree vertical angle to minimize the preferential flow. The suction cups were applied to each system, with 12 replicates covering an area of <0.5 ha. The suction cups were subject to a vacuum of 0.4 bars to gather free drainage water. Soil water samples were collected weekly from November to March and afterwards water subsamples from three suction cups were pooled together into one representing sample (four samples in total for each system and sampling date). Leachate samples were stored at −20 °C until the analysis. The soil water samples were photometrically analyzed using a dual-channel continuous flow analyzer (Skalar Analytical Instrument, Breda, The Netherlands) to determine the NO_3-N concentrations. Only the data for the NO_3-N fraction, as an indicator of groundwater pollution, was used to calculate the N leachate because it was by far the main component, and both the NH_4-N and organic N only marginally contributed. A climatic water balance model was used to calculate the amount of percolating water by using the (i) weather and soil data gathered from the experimental site (ii) the actual evapotranspiration [40] and (iii) the specific coefficients [41,42] to correct for the evapotranspiration.

2.4. Forage Yield and Quality

The forage yield was sampled by cutting the swards prior to grazing. Quadrats with an area of 0.5 m^2 were used to make 5 cm above ground cuttings. Ten quadrat samples of each subplot were randomly cut across the field by hand-operated clippers, collected in a bag and their weight was recorded immediately after harvesting. From the cut samples, two sub-samples of between 80–100 g were obtained. The first sub-sample was used to determine the dry matter (DM) content and was used for nutrient analyses. The second sub-sample was used for botanical composition and organized into three functional groups (grass, legumes and non-leguminous herbs). Samples were placed in an oven to dry at 60 °C for 48 h. The DM content and the forage yield (kg DM ha^{-1}) could then be determined. The dried forage samples were milled (Ultra centrifugal mill, ZM200, Retsch GmbH, Haan, Germany) to a particle size of 1 mm for analyses. The N content in the herbage was directly determined with an elemental analyzer (Vario Max CN, Elementar Analysensysteme, Hanau, Germany). The total crude protein (CP) was calculated by multiplying the respective N-content with a factor of 6.25. After grazing of the leftovers, the pasture and catch crops were sampled according to the procedure described above to calculate the net-grazing yield.

2.5. Field-N-Balance

The field-N-balance (kg N ha^{-1} $year^{-1}$) for the different treatments were calculated as the difference between the N_{input} and N_{output} using the following basic equation:

$$\text{Field-N-balance} = N_{input} - N_{output}, \quad (1)$$

where N_{input} is the amount of N applied through animal excreta, slurry application and BNF; and N_{output} refers to the amount of N exported through biomass. The symbiotic N_2-fixation of clovers was calculated using the empirical model described in Høgh-Jensen et al. [43]. The model provided by Høgh-Jensen includes the following parameters: sward age, sward composition and management.

2.6. Weather Data and Water Drainage

Weather data during the experimental years were recorded by a weather station (Vantage Pro2, Davies Instruments Corp., Hayward, CA, USA) close to the experimental sites (<1 km). The weather conditions during the study period (2017–2020) were contrasted between the years and they are presented in Table 2. The mean monthly rainfall for the study period was 59 ± 4.3 mm compared to the long-term average of 63 ± 3.8 mm. The winter leaching period (referred to here as October until March) of 2018/2019 received 298 mm of precipitation which was 82 mm less than compared to the long-term average of 380 mm, therefore it was considered to be a dry winter compared to the long-term average. The monthly average temperatures recorded during the study period ranged from −0.9 to 19.8 °C with an average of 10.2 ± 0.8 °C compared to the long-term average of 9.3 ± 1.7 °C [44].

Table 2. Monthly precipitation and average temperatures during the study period compared to the long-term total precipitation and average temperature (1991–2020) [44].

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
							Precipitation (mm)						
2017	80	57	51	47	42	116	102	61	75	124	91	82	928
2018	96	23	45	74	24	32	8	66	39	40	20	64	531
2019	41	39	94	22	61	74	54	48	100	85	79	49	746
2020	80	130	36	14	26	60	79	62	12	61	17	60	637
Long-term	67	51	52	38	50	64	83	78	62	74	65	71	754
							Temperature (°C)						
2017	1.3	2.8	6.5	7.2	13.3	16.3	16.7	16.9	13.9	12.0	6.3	4.2	9.8
2018	3.4	−0.2	1.7	9.8	14.8	16.8	19.8	18.6	14.6	11.5	6.4	5.2	10.2
2019	2.1	5.2	6.4	8.6	10.6	17.9	17.3	18.4	14.0	10.8	6.2	5.2	10.2
2020	5.7	5.7	5.6	9.0	11.2	16.6	15.8	19.7	14.8	11.3	7.9	4.4	10.6
Long-term	1.7	2.2	4.3	8.1	12.0	15.3	17.8	17.6	14.3	10.0	5.8	2.9	9.3

The accumulated percolating water that was calculated according to climatic water balance (see Section 2.3) over the duration of the current study is shown in Figure 1. In the second winter period (2018/2019), due to lower precipitation, the amount of percolating water was noticeably below the long-term average amount. The levels of precipitation in the winters of 2017/2018 and 2019/2020 were slightly higher compared with the long-term average. This will have a possible effect on nitrate loads due to the vertical movement of water. For this study, the weather conditions in the first and third winter could strongly increase the risk of N-leaching.

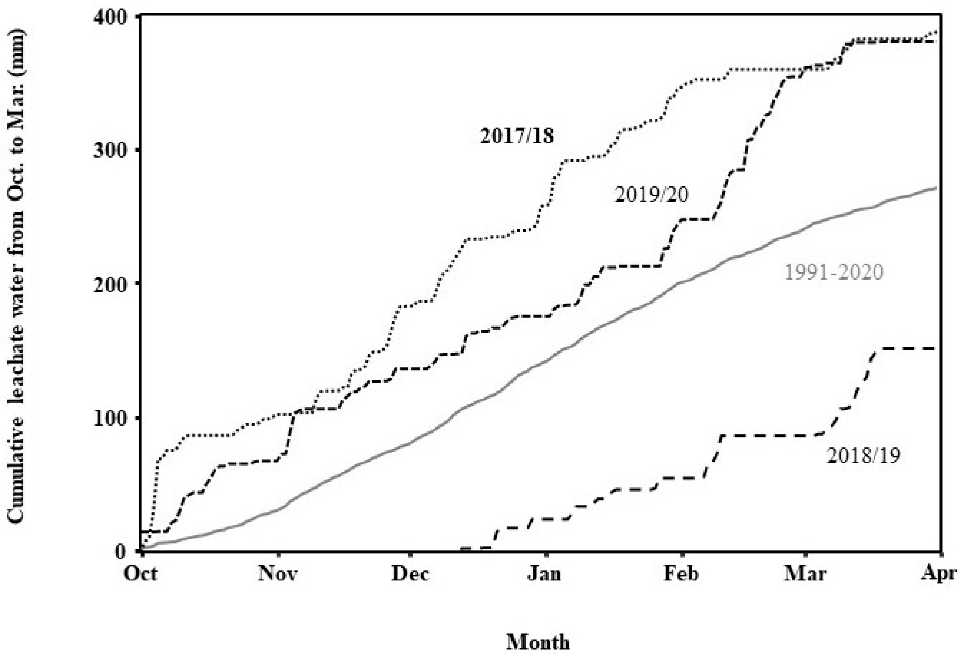

Figure 1. Accumulated percolating water (mm per m^2) over the three winter leachate periods (2017/2018, 2018/2019 and 2019/2020) compared to the long-term (1991–2020).

2.7. Statistical Analyses

The statistical software R 4.0.3 [45] was used to evaluate the data. The data evaluation started by defining an appropriate statistical linear model. Data distribution was assumed to be normal and heteroscedastic according to the different soil cultivation and fertilization treatments. These assumptions were based on a visual graphical residual analysis [46]. The statistical model included the selected System (S) and the experimental year (Y) as well as their interaction term as fixed factors. The significance of factors was declared at $p <= 0.05$. Based on this model, an analysis of variance (ANOVA) was conducted to test the hypothesis of the experiment. Furthermore, multiple contrast tests (e.g., see Bretz et al. [46]) were implemented in order to compare the several levels of the tested treatments. In order to evaluate a mathematical relationship between the N balance and NO_3-leaching, simple mathematical regressions were performed.

3. Results

3.1. Nitrogen Leaching

The NO_3-concentration in leachates (mg L^{-1}) and the N load (kg NO_3-N ha^{-1}) to ground- or drainage water were affected by the system ($p < 0.001$). An interaction was also observed between the system and experimental year ($p < 0.001$) and is presented in Table 3.

Table 3. Levels of significance among the tested factors: Systems (S), experimental year (Y) and the interaction (S × Y).

Factor	NO_3-Conc.	NO_3-Leaching	N-Yield	N-Balance
S	***	***	***	***
Y	n.s.	n.s.	***	**
S × Y	***	***	***	***

***: $p < 0.001$, **: $p < 0.01$.

The nitrate concentration and leaching loads over the trial period (2017/2018, 2018/2019 and 2019/2020) for the different systems are presented in Figure 2. The highest nitrate leaching was observed for the sward types GC_2y_grazed and CC60N_grazed, which occurred during winters 2017/18 and 2019/20 and reached nitrate losses of ~28 kg NO_3-N ha^{-1}. The lowest nitrate leaching across the different sward types were observed during the winter of 2018/2019 and ranged between 1.3 ± 0.2 and 9.8 ± 2.4 kg NO_3-N ha^{-1}. The highest nitrate losses of 28.7 ± 3.1 kg NO_3-N ha^{-1} $year^{-1}$ occurred in the GC_2y_grazed sward during year 2017/18, but during the second (2018/2019) and third (2019/2020) years it differed and was much lower at 4.0 ± 0.6 and 17.1 ± 1.7 kg NO_3-N ha^{-1} $year^{-1}$, respectively. The lowest nitrate losses occurred in year 2018/2019 with 1.3 ± 0.2 kg NO_3-N ha^{-1} $year^{-1}$ leached in the GC_0y sward (Figure 2).

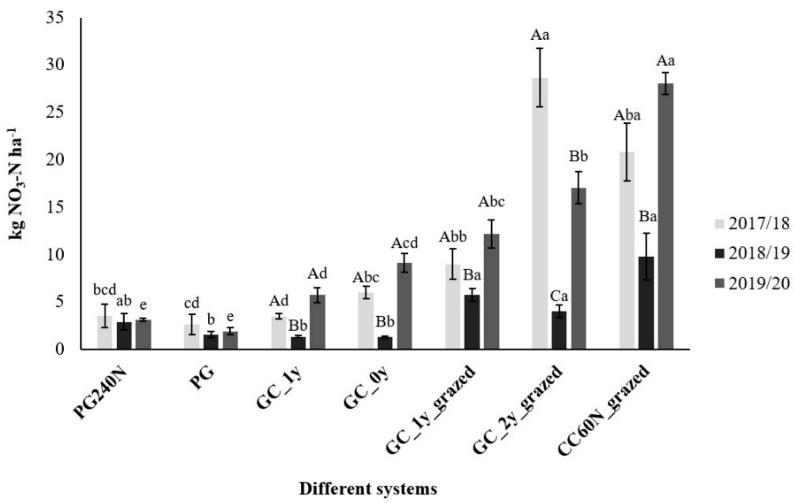

Figure 2. Average nitrate leaching losses (kg NO_3-N ha^{-1}) of the different systems investigated over three experimental years (2017/2018, 2018/2019 and 2019/2020). Different upper-case letters indicate significant inter-annual differences. Different lower-case letters indicate significant differences between the various sward types. Standard errors are shown.

The level of nitrate leaching losses differed markedly between the winter of 2018/2019 compared to the winter periods of 2017/2018 and 2019/2020. The mean cumulative nitrate leachate amounts averaged 8.5 ± 1.8 kg NO_3-N ha^{-1} over the trial period. The CC60N_grazed sward type showed average cumulative NO_3-N losses over the study period of 19.6 ± 5.3 kg NO_3-N ha^{-1}. In the permanent grassland (PG), lowest cumulative NO_3-N losses were recorded as 2.1 ± 0.3 kg NO_3-N ha^{-1}. Apart from the total nitrate losses, the NO_3-N concentration in the soil water is provided in Figure 3. The NO_3-N concentration ranged between 0.5 and 7.4 mg L^{-1} during the leachate periods and were found to be higher in the CC60N_grazed compared to PG. Regarding the three-year average only the CC60N treatment exceeded the WHO threshold (5.6 mg NO_3-N; 25 mg NO_3).

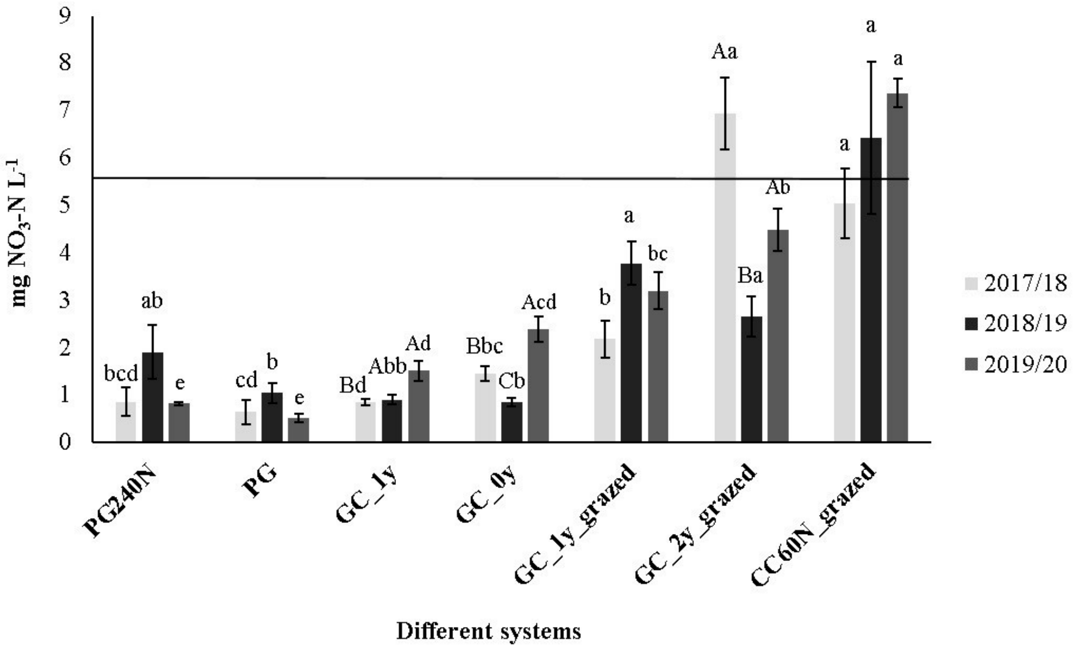

Figure 3. Average nitrate concentration in the soil water (mg L^{-1}) of the different systems investigated over three winter leachate periods (2017/2018, 2018/2019 and 2019/2020). The solid line indicates the threshold of 5.6 mg NO_3-N L^{-1}. Different upper-case letters indicate significant inter-annual differences. Different lower-case letters indicate significant differences between the various sward types. Standard errors are shown.

3.2. Herbage and Nitrogen Yield

The herbage yields for the different systems over the three years of study are shown in Figure 4. Inter-annual differences as well as differences between swards were observed ($p < 0.05$). The herbage yield was in the range of 0.9 to 12.4 t DM ha^{-1} over the three-year study period and was measured for the GC_0y (year 2017) and GC_1y_grazed (year 2019), respectively. The average values between the different swards ranged between 1.4 ± 0.1 (CC60N_grazed) to 11.0 ± 0.6 (GC_1y_grazed) t DM ha^{-1}. The average herbage yields were 6.4 ± 0.6, 8.2 ± 1.2 and 1.4 ± 0.1 t DM ha^{-1} for the permanent grasslands, grass-clover swards and the cover crop, respectively.

The N-yields of the different systems over the study period (2017–2019) are shown in Table 4. Inter-annual differences as well as differences between the swards were observed ($p < 0.05$). The N-yields were in the range of 181 ± 51 and 228 ± 66 kg N ha^{-1} during the study period. The years 2017 and 2019 were comparable with an average N-yield of ~220 kg N ha^{-1} over the different sward types. The lowest N-yield (40.6 kg N ha^{-1}) was observed in the CC60N_grazed swards and the highest (393.9 kg N ha^{-1}) in the GC_1y_grazed swards. The grazed grass-clover swards had an average of 378 ± 24 kg N ha^{-1} compared to the non-grazed grass-clover swards with 169 ± 57 kg N ha^{-1}, with the latter being comparable to the N-yields of 168 ± 18 kg N ha^{-1} from the permanent grasslands.

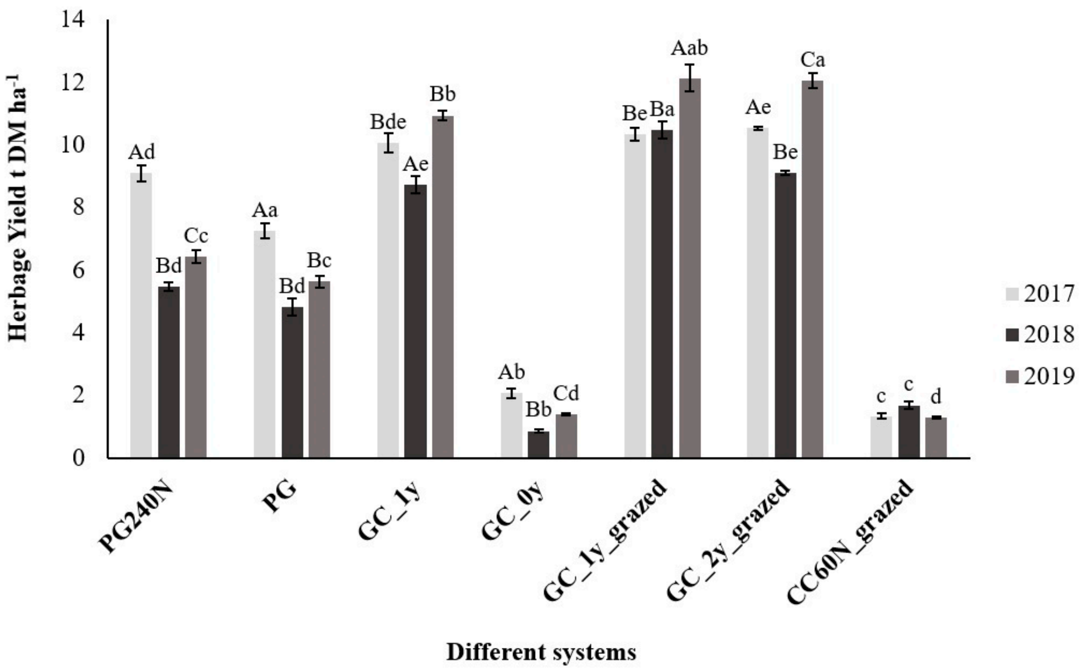

Figure 4. Average herbage yield (t DM ha^{-1}) of the different sward types investigated over the three years (2017, 2018 and 2019). Different upper-case letters indicate significant inter-annual differences. Different lower-case letters indicate significant differences between the various sward types.

Table 4. The N-yields (kg N ha^{-1}) of the different sward types investigated over the three years (2017, 2018 and 2019). Different upper-case letters indicate significant inter-annual differences. Different lower-case letters indicate significant differences between the various sward types. SEM are shown in brackets.

Year	PG240N	PG	GC 1y	GC_0y	GC 1y Grazed	GC 2y Grazed	CC 60N Grazed
	N-Yield (kg N ha^{-1})						
2017	229.5 ^{Acd} (12.6)	214.0 ^{Ad} (7.3)	285.5 ^{c} (13.1)	63.7 ^{Aa} (4.8)	362.4 ^{Be} (1.2)	363.7 ^{Ae} (6.1)	36.9 ^{b} (1.9)
2018	122.7 ^{Bd} (5.3)	123.4 ^{Bd} (10.3)	288.8 ^{e} (8.7)	23.9 ^{Bb} (2.0)	378.4 ^{Ba} (8.8)	284.6 ^{Be} (10.1)	46.4 ^{c} (2.9)
2019	160.2 ^{Cb} (9.2)	159.0 ^{Bb} (9.2)	316.4 ^{a} (2.9)	38.8 ^{Cd} (1.5)	440.8 ^{Ac} (16.0)	443.0 ^{Cc} (8.9)	38.5 ^{d} (0.7)

3.3. Nitrogen Balance

The calculated field-N-balances were positive in all different swards over the study period. Field-N-balances varied widely between different sward types, ranging from 11 ± 4 to 276 ± 21 kg N ha^{-1} and are displayed in Table 5. The values were generally lower for the permanent grassland (PG) compared to the permanent grassland that received slurry (PG240N) and were 11 ± 4 compared to 149 ± 8 kg N ha^{-1}, respectively. The highest average field-N-balance of 210 ± 37 kg N ha^{-1} were observed in the grazed grass-clover swards compared to the grass-clover swards that were not grazed, with a field-N-balance of 57 ± 13 kg N ha^{-1}.

Table 5. The N-balance of the different sward types investigated over the three years (2017, 2018 and 2019). Different upper-case letters indicate significant inter-annual differences. Different lower-case letters indicate significant differences between the various sward types. SEM are shown in brackets.

	PG240N	PG	GC 1y	GC 0y	GC 1y Grazed	GC 2y Grazed	CC 60N Grazed
				Yearly Inputs (kg N ha^{-1})			
2017	355.5 (5.7)	222.8 (8.5)	383.5 (18.9)	58.0 (5.1)	379.1 (12.2)	277.9 (5.1)	60.0 *
2018	278.9 (3.0)	121.6 (9.5)	358.7 (26.0)	24.6 (3.1)	374.2 (18.7)	159.0 (11.9)	60.0 *
2019	305.7 (4.8)	165.3 (9.5)	404.0 (5.8)	38.6 (1.3)	479.1 (19.5)	373.2 (3.4)	60.0 *
				Yearly Outputs (kg N ha^{-1})			
2017	221.8 ^{Ae} (12.2)	206.7 ^{Ae} (7.0)	285.5 ^{a} (13.1)	17.6 ^{Ab} (1.3)	118.4 ^{Bd} (1.4)	123.7 ^{Ad} (2.9)	10.3 ^{c} (0.5)
2018	118.5 ^{Be} (5.1)	119.2 ^{Bde} (10.0)	288.8 ^{c} (8.7)	6.6 ^{Ba} (0.6)	125.8 ^{Be} (5.2)	95.4 ^{Bd} (4.4)	12.9 ^{b} (0.8)
2019	153.3 ^{Cc} (9.8)	150.9 ^{Bc} (10.1)	316.4 ^{a} (2.9)	10.8 ^{Cb} (0.4)	161.2 ^{Ac} (5.9)	159.4 ^{Cc} (2.9)	10.7 ^{b} (0.2)
				N-balance (Inputs-Outputs) (kg N ha^{-1})			
2017	133.7 ^{Acd} (8.3)	15.8 ^{b} (4.1)	98.0 ^{c} (8.3)	40.4 ^{Ae} (3.9)	260.7 ^{Ba} (11.8)	154.1 ^{Ad} (3.0)	49.7 ^{e} (0.5)
2018	160.4 ^{Bb} (2.2)	2.4 ^{d} (4.9)	69.9 ^{ce} (19.0)	17.9 ^{Bcd} (2.5)	248.4 ^{Ba} (14.7)	63.7 ^{Be} (7.7)	47.1 ^{e} (0.8)
2019	152.3 ^{Abd} (7.3)	14.4 ^{b} (2.5)	87.6 ^{c} (8.7)	27.8 ^{Cf} (0.9)	317.9 ^{Aa} (13.9)	213.8 ^{Ce} (4.6)	49.3 ^{g} (0.2)

* Slurry application was applied.

The field-N-balance was used to investigate the effect of different management systems on N-leaching. The correlation between the field-N-input and the NO_3-N-losses are shown in Figure 5. A clear relationship was not found between the field-N-input and the NO_3-N-losses.

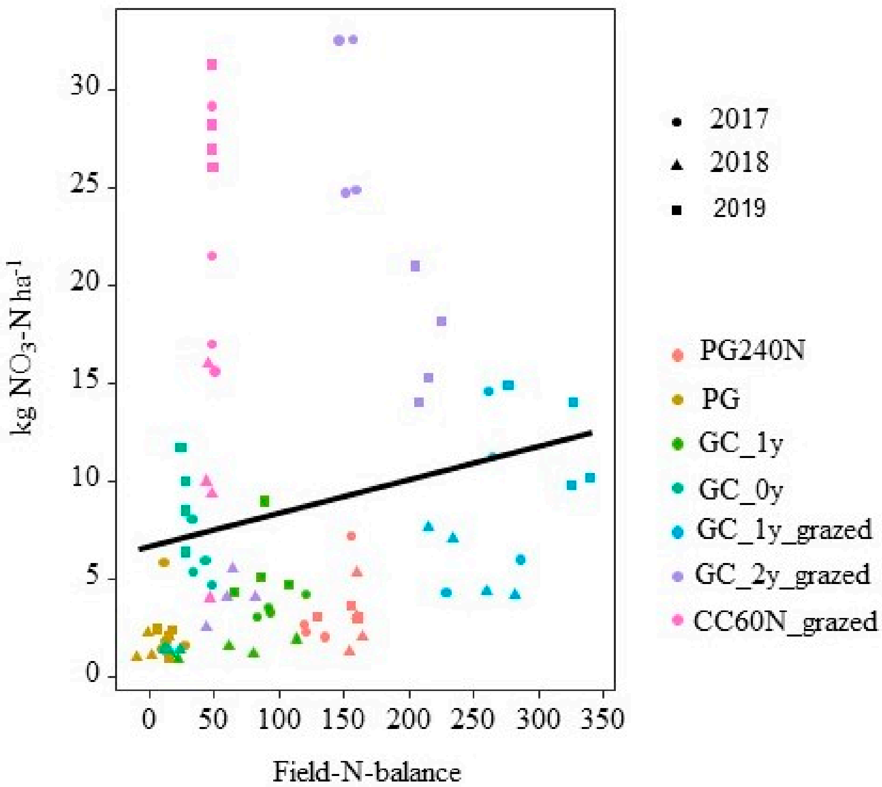

Figure 5. The relationship between the field-N-balance and NO_3-leaching (kg NO_3-N ha^{-1}) of the different systems used in the study.

4. Discussion

4.1. Nitrogen Leaching Losses

Nitrate leaching following the swards in the current study may be generally divided into two groups: (1) low leaching (<10 kg N ha^{-1}) consisting of the permanent grasslands (PG, PG240N) and grass-clover swards (GC_1y, GC_0y and GC_1y_grazed), and (2) medium leaching (10–20 kg N ha^{-1}) consisting of a grass-clover sward and a catch crop which were both under grazing (GC_2y_grazed and CC60N_grazed). The amount of N-leaching depends on the mineral nitrogen access, land-use, soil type as well as the prevailing weather conditions and the length of the growing period [37,47]. It is clear from the results that 2018/19 had less precipitation compared to the other years which resulted in substantially lower amounts of N leached during this winter (Figure 2). The results from the current study are considered to be low as compared to various European studies that had values between 15 and 50 kg NO_3-N ha^{-1} $year^{-1}$ [2,48].

Silage cuts were obtained from swards (PG, PG240N and GC_1y) and used to feed cows during winter. This allows for the N to be removed in herbage and fed off-site which avoids N returns to pasture by avoiding any grazing in situ [2,47,49]. This decreases the risk of NO_3-N leaching losses over the winter period. Cutting-only systems would be the most advantageous in terms of NO_3-N leaching, however, combining cutting and grazing is a preferred technique to pure grazing systems [2,50]. Our results support this and indicated the NO_3-N leaching losses to be lower in the permanent grasslands compared to the combined cutting and grazing and mostly grazed swards (PG, PG240N < GC_1y, GC_0y < GC_1y_grazed, GC_2y_grazed, CC60N_grazed). This agrees with a study conducted by Kunrath et al. [47] where the amplitude on nitrate concentrations was lower for grassland.

Intensive tillering as a result of management allows for new root development which assists in nutrient uptake. A well-established root system can contribute considerably to N uptake which affects the rate of N losses to the environment [47]. Even though the permanent grassland (PG240N) received fertilizer (240 kg N ha^{-1}), the fertilization did not cause significant increases of NO_3-N losses. This indicates that these swards (>20 years) are well established with a healthy root system which perform their function to absorb nutrients. Furthermore, roots are key components of C sequestration due to their longer residence time in soils [51].

The grass-clover-leys in the first year of production (GC_1y) contained the lowest NO_3-N losses compared to the other grass-clover-leys (GC_0y, GC_1y_grazed and GC_2y_grazed) from this study. The N cycle is generally closed in the short-term while these swards still grow, and during the first year in particular, they invest high amounts of nitrogen into the rooting system. Chen et al. [38] demonstrated, for the same site, fBNPP values of 0.4, indicating that 40% of the total DM and nitrogen uptake of swards are stored in the rooting system, resulting in an additional C storage and N storage of 1000 and 100 kg per year, respectively [39], therefore N leaching is very low. Moreover, leys were established after cereal production that received extensive N-fertilization, which caused a low N-status in the soil. This was also observed in the current study in the swards which were newly established (data not shown). Furthermore, grass-clover-leys can have several and contrasting effects on NO_3-N leaching losses. Even though BNF can be a major source of N for crops, it can also add to soil fertility and subsequently lead to NO_3-N leaching losses [52]. This was also observed in the current study especially when the swards are subjected to additional N-inputs from grazing animals in the second ley year. This is also in accordance with data from Chen et al. [38] who indicated that fBNPP values are much higher in the first (0.6) than in the second (0.4) production year. It is therefore very likely that the N uptake capacity of the rooting system is reduced from the second production year onwards.

The risk for nitrogen leaching increased through grazing and was highest in the grazed swards due to animal excreta-N when compared to cut-only swards. Large volumes of urine are deposited back onto pasture during grazing which can be greater than the capacity of pasture plants to assimilate [26]. Dairy cows metabolize less than ~25% of their N-intake into milk output and can excrete as much as ~75% [53]. Therefore, excess N can accumulate in the soil during autumn, which typically leads to higher N-leaching losses during surplus winter precipitation. This was shown in the cover crop sward under grazing conditions and fertilization (60 kg Nha^{-1} before sowing in August).

The inclusion of forage legumes in pasture mixtures can reduce the environmental impact of milk production by supplying additional N via BNF and thereby reducing N-leaching through more effective N-cycling in these forage legume systems [15,17,19]. However, a clover-N feedback mechanism exists whereby the proportion of legumes and consequently BNF decreases in grass-legume swards when N inputs increases [48,54]. For this reason, there will be a lower input from BNF when N inputs from excreta occur. This was also the case in the current study which had a lower clover contribution in the swards that were under grazing. Higher N leaching losses were observed in the current study from grazed grass-clover-leys (on average 8.98 kg NO_3-N ha^{-1}) compared to the non-grazed grass-clover-leys (on average 3.53 kg NO_3-N ha^{-1}). This could be explained by a reduction in BNF in the grazed grass-clover-leys as a consequence of recycled animal excreta. Furthermore, the introduction of deep-rooting legumes such as red clover and bird´s-foot trefoil (*Lotus corniculatus*) into perennial ryegrass swards has a further potential to reduce N-leaching. However, the red clover contribution declined with sward age (second ley year) as a result of its lower grazing tolerance compared with white clover.

Jersey cows grazed the swards in the current study on the research site. The currently implemented grazing strategies rely on a lower herbage (1 t ha^{-1}) and between 8–10 grazing cycles compared with grazing strategies in the 1990s which contained higher herbage and provided fewer grazing cycles. On one hand, this suggests that much more urine-N is evenly excreted onto pasture over the grazing period and on the other hand, that the nitrogen uptake capacity of the swards is enhanced [55]. Jersey cows are often seen as more environmentally friendly compared to Holstein cows as they excrete less nutrients in urine per urination [56,57]. Nonetheless, this might explain the higher N-leaching in the grass-clover-ley in the second year of production due to a decrease in clover contribution to the sward due to increased N from urine. However, N-leaching values from the current study are still very low compared to the published data from northern Germany for the silage maize systems, which represents forage production for a high input-high output dairy system [58], suggesting that even though excreta affect the rate of N-leaching losses, it was still lower than the crop demand.

The risk associated with N-leaching depends on the rate of mineralization and the successful uptake of N by the following crop [48]. Catch crops have been shown to be effective at reducing N-leaching losses [36,49,59]. However, a catch crop needs to be established early enough to absorb a considerable amount of N before leaching begins in winter. The results from the current study indicated that the cover crop under grazing and fertilization had the highest amount of N-leaching losses. However, even with the highest amount of N-leaching (~20 kg NO_3-N ha^{-1}) compared to the other swards from this study, this level is still below other values reported in the literature (10–80 kg NO_3-N ha^{-1}) which places our findings at the lower end [1,48,52]. The advantage in reducing NO_3-N leaching losses is derived in high N removal in herbage and low N loads recycled from cow excreta [48]. Additional mitigation could be achieved through the biomass harvesting of catch crops instead of grazing by animals. Furthermore, even though regional services suggest extensive N-fertilization of catch crops prior to seeding or shortly after succeeding cereal crops, the fertilization of grazed catch crops should be reconsidered because of the high level of N losses.

Field management should focus on increasing the N uptake during autumn to decrease N-leaching losses during winter [35,52]. High mineral N and mineralization of residues at the end of the vegetation period should be avoided. The potential N-leaching can be reduced by establishing catch crops earlier, but its benefits vary and depend on the weather conditions [35]. However, N-leaching can increase with the continuous use of catch crops when winter cereals cover the soil during winter and autumn [52].

4.2. Field-N-Balance

The only information that is often available at the field-, farm- and regional level, is the field-N-balance which is then used to estimate risks associated with N-leaching. The field-N-balance was positive in all the different swards and ranged between 11 and 150 kg N ha^{-1} $year^{-1}$. These values are considerably less than values (150–250 kg N ha^{-1} $year^{-1}$) previously reported for the Netherlands and Germany [60], with the exception of the grazed grass-clover sward (GC_2y_grazed) in the current study with a field-N-balance of 276 kg N ha^{-1} $year^{-1}$.

The field-N-balance was especially high in the grazed grass-clover swards due to direct deposition of animal excreta and only one removal of N via harvested biomass. This was in accordance with Eriksen et al. [48] who reported the highest amount of surplus N on grazed plots. The high soil-N status as a result of high N inputs in the grazing management systems may explain the high N contents in the grazed grass-clover swards [61]. The presence of clovers can increase N yields significantly compared to only grasses [62]. Additionally, frequent grazing and biomass cuts can also increase N fixation which leads to high N inputs [63]. The grass-clover swards, which were not subjected to grazing and therefore did not display high N returned through excreta, possessed a low associated field-N-balances of 85 and 29 kg N ha^{-1} $year^{-1}$, respectively. This indicates that these grass-clover swards which received low N inputs in terms of fertilization have a higher efficiency in N transfer and NUE [64]. However, the regression equations did not confirm a strong correlation of N surplus and N leaching for arable-ley systems managed with low rates of external N supplied. The same limited correlation between surplus N and N-leaching was observed by Eriksen et al. [48]. One important factor is the build-up of soil organic matter during the ley years, which can achieve up to 1.3 t of carbon ha^{-1} $year^{-1}$ in the upper soil layer (0–30 cm) after its establishment. During the proceeding years, a decrease in sequestration rates is usually observed for permanent grassland, however, it is still a positive trend with increments of ~0.3 t C ha^{-1} $year^{-1}$ over a 20-year period [65]. If a C/N of 12 is considered, it indicates an N sequestration rate of, on average, 100 kg N ha^{-1} $year^{-1}$ for leys and 23 kg N ha^{-1} $year^{-1}$ for permanent grassland, which explains most of the residual N in the different systems.

The clover contents found in the permanent grasslands was still high (data not shown) and may help to explain the high N-balance in the PG240N system due to the combination of fertilizer and BNF. Moreover, the increased amount of fertilizer could result in higher N supplied from organic N-sources. Even though the PG240N received fertilizer, no differences were observed between the N yields from the permanent grasslands. This could be due to the process of apparent N transfer whereby the N-fixating clovers increased soil-N availability which improves the N uptake of the grasses in the PG system without an added fertilizer [61].

Catch crops have been shown to reduce N-leaching [35]. However, the highest N-leaching was associated with the cover crop even though it had a low field-N-balance. A possible reason could be grazing, and consequently high N returns through excreta. Urinary N may typically contribute 70–90% to total N lost through leaching because of a much larger specific rate of N application, compared to fertilizer [66]. Moreover, the grazing of catch crops late in the year causes trampling patches, which triggers the decay of residual plant biomass. Consequently, the N-uptake through the catch crop cannot be entirely maintained as a potential source of N for the catch crop in the next spring in ley-arable systems. Thus, to make use of grazed catch crops on this system's basis seems to be questionable as on one hand, it provides herbage for dairy but on the other hand it triggers N shortages for subsequent cereal production and increases the N load to groundwater. The permanent grassland under slurry-fertilization resulted in a high field-N-balance. This was as a result of N-inputs through BNF and slurry-fertilization which added to >300 kg N ha^{-1} $year^{-1}$. This exceeded the N demand for pasture plants and resulted in an N surplus of up to 149 kg N ha^{-1} $year^{-1}$. This means fertilizer planning is necessary while accounting for the BNF.

Our results indicated that across all the treatments, a low level of N surplus was observed on the field-level. This can be attributed to several factors. In the current farming system (low-input system) a high share of N is stored as nutrients to be utilized by the sub-sequent catch crop. This is contradictory to the high-input high-output confinement system based on forage maize and high rates of concentrate feeding. It is therefore possible that in our low-input system, the high soil organic matter improves the soil properties and its functions. It was also suggested by Crème et al. [67] that the soil organic matter can counteract GHG emissions and enhance C sequestration. A study conducted by Nyameasem et al. [34], on the same experimental site, reported low levels of N_2O emissions which further indicates the effective use of N in the low-input system [20]. With regard to the N on a farm-level, a low-input ley-systems based on grazing allows for high productivity in combination with high biodiversity effects [68], low GHG emissions [16,34] and milk production with a low carbon footprint, thereby resulting in eco-efficient dairy systems [69]. These low-input systems could therefore serve as a platform in order to reduce the negative environmental effects associated with dairy farming in northern Germany which will adhere to the European Union Nitrate Directive [8], the Water Framework Directive [9] and the Groundwater Directive [10], organizations that aim to protect both surface and groundwater from agricultural use.

5. Conclusions

This study demonstrated that the combination of fertilization and grazing of a cover crop caused the highest level of N-leaching, while the omission of fertilization and herbage-N removed as cuts for silage substantially reduced leaching losses. Grazed leys indicated high herbage production for dairy systems and the highest field-N-balances. However, high field-N-balances of grazed grass-clover-leys were not an appropriate indicator to predict N-leaching losses as high amounts of N are sequestered in the soil and plant residues. Thus, in ley-arable systems where the intensity of external N supply is low, a high proportion of N for the arable unit is derived from the plant residuals of leys. In conclusion, this low-input system can still maintain high productivity while simultaneously reducing the negative environmental effects associated with dairy farming such as N-leaching which can serve as a solution to the EU Nitrate Directive which aims to protect groundwater from nitrate pollution that is caused by agriculture.

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