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Review

The Effects of Manure Application and Herbivore Excreta on Plant and Soil Properties of Temperate Grasslands—A Review

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Abstract: This review provides an overview of grassland studies on the effects of manure application and herbivore excreta on plant and soil properties in temperate grasslands. Grass biomass from grazing or mowing is mainly used for animal products such as milk or meat, as well as for energy or raw materials for biorefineries. Manure application or grazing has a significant impact on several plant and soil properties. There are effects on soil chemical properties, such as increased carbon sequestration, improved nutrient availability, and increased pH. Additionally, several physical soil properties are improved by manure application or grazing. For example, bulk density is reduced, and porosity and hydraulic conductivity are greatly improved. Some biological parameters, particularly microbial biomass and microbial and enzyme activity, also increase. The use of manure and grazing can, therefore, contribute to improving soil fertility, replacing mineral fertilizers, and closing nutrient cycles. On the other hand, over-application of manure and overgrazing can result in a surplus of nutrients over plant needs and increase losses through emission or leaching. The lost nutrients are not only economically lost from the nutrient cycle of the farm but can also cause environmental damage.

Keywords: organic fertilization; grazing; nutrient cycle; soil fertility

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1. Introduction

Currently, 31.7% of the European Union's utilized agricultural area is used as grassland [1], which is mainly of anthropogenic origin [2]. Grassland use has developed primarily where site conditions are unfavorable for crop production. For example, sites may be too wet, too dry, too steep, or too stony [3,4]. Grasslands provide several ecosystem services to human society, such as primary production, carbon sequestration, biodiversity conservation, flood control, water filtration and purification, and recreation and tourism [5]. Managed grasslands play an essential role in securing food supplies [6]. In addition to food production, grass biomass can be used as a feedstock for biogas production and as a solid biofuel, as well as a raw material for several other bioproducts [7,8].

Since the last century, and especially since 1970, the human population has grown rapidly [9], which has led to a growing demand for animal products, such as increased meat and milk consumption [10,11]. Therefore, in order to produce more livestock products, the productivity of grassland has often been increased [12]. Livestock production—especially dairy production—is extraordinarily important for human food production [13] and will continue to intensify to meet growing demand [10]. In addition to milk and meat, livestock production also produces manure [14].

The increasing amount of manure makes it necessary to reconsider manure as a valuable nutrient source rather than a waste compared to mineral fertilizers [15]. Nutrients removed as forage or feed and not replaced by crop residues, atmospheric deposition, or N fixation must be returned through fertilizer inputs; otherwise, soil fertility and productivity will decline [16]. When manure is applied to the soil, it provides a slow-release source of several nutrients that improve soil fertility and support plant growth [17,18]. Organic fertilizers contain the same basic nutrients, such as N, P, and K, as mineral fertilizers [19]. The use of organic manure can reduce the need for synthetic chemical fertilizers, which can be expensive and have environmental drawbacks [15]. In addition, mineral P fertilizers derived from rocks are a finite resource [20]. Therefore, the use of nutrient-rich manure is a sustainable alternative that reduces chemical dependency [15,21]. Consequently, organic manure can reduce input costs for farmers [22]. It is in line with the principles of agroecology and promotes environmentally friendly, resource-efficient, and long-term sustainable agriculture [15]. As an additional result, it can open up markets for organic and sustainably grown products, which often command higher prices.

Organic matter in manure is also rich in carbon [23]. When incorporated into the soil, it can contribute to carbon sequestration, helping to mitigate climate change [23]. Organic manure helps improve soil structure and water-holding capacity [24]. Therefore, it increases the soil's ability to retain moisture and nutrients, reducing the risk of soil erosion and increasing drought resistance.

In addition to the many positive effects of manure application, there are also negative aspects to consider. Manure spreading can produce strong odors that can be unpleasant for people living near agricultural land [25]. Spreading manure evenly over grassland can be technically challenging, especially on uneven terrain. Uneven application can result in patchy plant growth [26]. Proper timing of application is also very important so that (1) plants are in the growing season and able to take up the nutrients being released, and (2) weather and soil conditions are appropriate so that the amount of manure applied remains in the soil and does not wash out [27]. Improper manure application and overgrazing can lead to overfertilization and soil compaction, both of which can severely degrade soil and water quality [28,29]. It can also result in feed contamination, which degrades feed quality and can lead to reduced feed intake and poor animal performance [30].

Fertilization with organic fertilizers applied directly during grazing as animal excreta or in the form of manure is a common practice in grassland management [31]. The nutrient content of manure needs to be measured or determined prior to application, whereas nutrient and organic matter inputs during grazing are more or less unknown and very heterogeneously distributed [32]. The interactions between applied nutrients and organic matter of organic fertilizers, soil fertility, plant growth, and herbage nutrient content are complex due to many biological, biochemical, and physical processes [33].

The objective of this review is to provide an overview of the effects of organic fertilization on the properties of temperate grasslands. In addition to changes in properties, topics covered in this paper include the basics of grasslands and their use and factors for optimizing the effects of fertilization by adjusting management practices.

2. Grassland Management

2.1. Grassland Use

Typical uses of grassland include mowed meadows, grazed pastures, and mown pastures as a combination of both [3,34,35]. Mown pastures are grasslands that are harvested by mowing several times per year [36] to produce hay or silage [35,37]. Pastures are grasslands that are grazed year-round or for a limited period, usually spring and summer. Typical grazing animals are cattle, sheep, horses, and goats [3]. During grazing, up to 90% of the nutrients consumed by ruminants are returned to the soil in the form of excreta [38]. Mown pastures are usually both grazed and mowed in the same year [39], but sometimes they are mowed or grazed only once a year [2] and typically mowed once at the end of the season [34].

2.2. Intensity of Grassland Management

Currently, there is a wide variation in the management intensity of grasslands. It ranges from extensive to intensively managed grasslands [2,40]. This depends on the amount of fertilizer, mowing frequency and/or grazing duration, and livestock density [34].

Table 1 shows typical levels of land use intensity in terms of fertilization, harvest, and livestock density. Extensive grasslands provide more regulating ecosystem services than intensive grasslands and are, therefore, often part of agri-environmental or compensation programs that prohibit or limit fertilization rates and require a late harvest date [6]. In contrast, very high forage quality is achieved on intensively managed grasslands [41].

Table 1. Land use intensity of grassland.

Management	**Intensive Grassland**	**Medium Intensive Grassland**	**Extensive Grassland**	**Reference**
Cutting frequency per year	4 and more	2–3	1	[36]
Quantity of fertilizer applications per year	Up to 5	3–4	0–2	[42,43]
Amount of fertilizer applications per year	Up to 640 kg N ha^{-1}	n.s.	0–181 kg N ha^{-1}	[42,44–46]
Grazing intensity	3.4 LU	1.8 LU	0.8 LU	[47]
Input of herbivores	144 kg N ha^{-1}	n.s.	128 kg N ha^{-1}	[48]

n.s.: not specified.

As the number of cuts increases, the intensity of grassland management increases. The variation ranges from extensive grassland with one cut per year to four cuts and more for intensively managed grassland. Two to three cuts are considered as medium-intensive management [36].

Another characterization of management intensity is based on the number and amount of fertilizer applications. While pastures are mainly fertilized with livestock excreta [49–51], meadows and mown pastures are typically fertilized with both organic and mineral fertilizers [52]. In extensive systems, zero to two fertilizer applications are typical [42], and up to five applications per year in intensively managed grasslands [43]. A typical application rate in intensive farming systems in studies ranged from 181 kg N ha^{-1} [46] to 640 kg N ha^{-1} [45]. For extensive management, it has been reported that there is no fertilization [44] to 97 kg N ha^{-1} [42].

The grazing intensity of pastures ranges from 500 kg live weight or two heifers per ha as extensive management to 1000 kg live weight or four heifers per ha as intensive management [53]. Another classification of grazing management intensity is based on livestock density, referred to as livestock units (LU). According to Wang et al. [47], 0.8 LU is considered low intensity, 1.8 LU as medium intensity, and 3.4 LU as high intensity. Typical husbandry systems for extensive grazing in Europe are suckler cows [42] and sheep [54,55]. Diary husbandry is the most common form of intensive grazing system [42,54,56]. A typical average N input from herbivores under intensive grazing is 144 kg N ha^{-1}, and under extensive grazing, it is 128 kg N ha^{-1} and 117 kg N ha^{-1}, respectively, for organic farming [48].

While intensive management systems result in higher yields [57], energy consumption, e.g., for grass drying and the use of mineral and organic fertilizers, are much higher compared to extensive management systems [48].

2.3. Conventional versus Organic Farming

Grassland farming systems are managed in both conventional and organic manner. Conventional farming systems use multiple fertilizers, herbicides, and pesticides. This results in higher yields. On the other hand, the costs are higher compared to organic farming, and the impact on the environment can be negative. Organic farming aims to reduce external inputs, using organic sources as nutrient inputs and promoting sustainable soil management. However, the yield of organic farming systems is often lower, resulting in higher product prices [58]. Compared to intensive conventional farming, organic farming requires about half the product-related energy inputs; e.g., organic farms in Germany use 65% less energy than conventional farms [48]. In particular, fertilizer use is reduced to about two-thirds compared to conventional farming [59].

3. Application of Organic Fertilizers

3.1. Organic Fertilizer Properties

The nutrient content of organic fertilizers varies depending on the type of organic fertilizer [60], livestock species [61,62], husbandry system [63–65], and feed composition [65–67].

The types of organic fertilizers most often used in agriculture are as follows:

1. Slurry—a combination of the liquid and solid fractions of excreta;
2. Semi-solid manure—mainly the feces separated into liquid and solid fractions;
3. Solid manure, also called farmyard manure—feces combined with litter or straw [68].

According to Gisiger [60], solid organic fertilizer has the highest C and P content, while the amount of N and K in urine is higher. An increase in the solid fraction of the organic fertilizer leads to a higher P content and a simultaneous decrease in K and N [60,64]. Therefore, N (45–80%) and K (70–90%) are mainly excreted in urine, and between 20% and 55% of N, together with more than 95% of P and Ca are excreted in solid manure [62]. Composted manure has a lower C content but contains more N than non-composted manure [24]. The feed composition—especially protein and cellulose contents—affected not only the amount of nutrients but also the microbiological composition in organic fertilizers [66]. Higher protein content leads to increased N and P content [65] and has a positive effect on microbial communities [66]. However, ammonia (NH_3) volatilization increases [65,67]. The higher energy content of feed with more protein reduces the dry matter (DM) content of manure due to higher digestibility [65]. A lower protein content leads to a decrease in N [65,66] and S and a lower amount of NH_3 [66]. Other components such as Ca, Mg and Na are correlated with the amount of total N. van der Stelt et al. [65] found that the higher the N content, the lower the amount of free Ca and Mg due to exchange processes with ammonium (NH_4). Mg content increases with increasing K due to a negative effect on the digestibility of Mg [65].

Table 2 summarizes the results of the nutrient content of different types of manure from the Manure Standards Project (https://msdb.netlify.app/ accessed on 5 December 2023).

Table 2. Nutrient contents in different types of manure (laboratory analysis results of Manure Standards Project: https://msdb.netlify.app/ accessed on 23 October 2023).

Animal Group	Manure Type	DM (%)	SD (%)	n	Tot-N (% FM)	SD (% FM)	n	Tot-P (% FM)	SD (% FM)	n	K (% FM)	SD (% FM)	n	pH	SD	n
Beef cattle	deep litter	26.99	3.78	11	0.55	0.21	11	0.08	0.04	11	0.67	0.28	11	8.68	0.40	4
Beef cattle	semi-solid manure	15.74	1.47	7	0.30	0.06	7	0.13	0.04	7	0.00	0.00	0	8.24	0.40	7
Beef cattle	slurry	8.78	1.72	13	0.34	0.09	13	0.08	0.02	13	0.41	0.08	13	7.78	0.40	12
Beef cattle	solid manure	26.86	12.38	7	0.57	0.15	7	0.11	0.01	7	0.62	0.27	7	8.47	0.38	7
Dairy cows	semi-solid manure	15.62	3.24	46	0.32	0.07	46	0.12	0.05	46	0.06	0.00	1	7.78	0.65	45
Dairy cows	slurry	8.36	2.99	79	0.28	0.11	79	0.06	0.02	79	0.28	0.10	78	7.63	0.38	74
Dairy cows	solid manure	21.57	7.19	56	0.50	0.18	56	0.13	0.06	56	0.58	0.23	40	8.38	0.49	53
Suckler cows	deep litter	23.22	4.64	14	0.57	0.17	14	0.10	0.04	14	0.82	0.37	14	8.39	0.56	10
Heifers/calves	semi-solid manure	15.78	1.99	18	0.31	0.07	18	0.13	0.04	18	0.00	0.00	0	8.01	0.56	18
Heifers/calves	solid manure	21.44	7.07	27	0.41	0.08	27	0.13	0.05	27	0.51	0.16	12	8.06	0.54	27
Pigs integrated	deep litter	27.49	4.14	5	0.70	0.14	5	0.22	0.08	5	1.17	0.66	5	8.40	0.40	5
Pigs integrated	liquid fraction	2.69	0.82	5	0.09	0.09	5	0.04	0.05	5	0.00	0.00	0	7.81	0.26	5
Pigs integrated	slurry	3.29	1.54	7	0.29	0.15	7	0.08	0.04	7	0.15	0.03	6	7.32	0.44	7
Pigs integrated	solid manure	25.72	5.72	7	0.47	0.28	7	0.25	0.16	7	0.33	0.08	3	8.17	0.71	7
Fattening pigs	slurry	5.49	3.06	34	0.44	0.21	34	0.08	0.04	30	0.21	0.07	28	7.61	0.50	31
Broilers	deep litter	54.77	16.94	14	2.65	0.78	14	0.58	0.13	13	1.39	0.44	13	6.40	1.21	8
Laying hens	solid manure	43.25	22.98	11	1.46	0.53	11	0.47	0.35	11	0.71	0.18	3	7.81	0.91	9
Sheep	deep litter	33.28	16.93	11	0.68	0.27	11	0.17	0.07	11	0.99	0.40	11	8.86	0.34	10

% FM percent fresh matter, SD: Standard deviation.

3.2. Application Techniques and Their Effects

Several techniques are available for organic fertilizer application that have different emission losses of nutrients, especially N [69]. Typical techniques are broadcast applications on the soil surface, such as splash plate or band spreading techniques, low trajectory slurry applications, such as trailing shoe or shallow injection methods [70,71], and narrow band applications [72]. Huijsmans et al. [72] found that NH_3 losses during slurry application were reduced by up to 74% using shallow injection compared to broadcast application. Groot et al. [73] confirmed that shallow injection was always the most efficient application method in terms of N losses. Overall, NH_3 volatilization of total N varied from 27% to 98%

with broad band application, 8% to 50% with narrow band application, and 1% to 25% with shallow injection. Precision application techniques such as shallow injection can be used to reduce NH_3 losses not only for manure and slurry [74] but also for other organic fertilizers such as digestate [75]. Due to reduced N losses, more N was available for plants when slit and injection techniques were used [32].

It should be noted that in some European countries, such as Germany [76] and the Netherlands, the use of some application techniques is restricted [32]. High-emission techniques such as broad band application are prohibited in these countries, and therefore the use of low-emission techniques is mandatory [32,76].

Table 3 provides an overview of N losses, N recovery, and N loss reduction with different application techniques in temperate grasslands.

Table 3. Overview N losses in percent (%) with different application techniques of manure on temperate grassland.

Application Technique	Total N Losses by NH_3 Volatilisation (%)	Reduction in N Losses (%)	Reference
Broadcast application	27–98	-	[73]
	27.3–84.5	-	[77]
	21	-	[72]
	19.1	-	[75]
	40	-	[78]
Cattle slurry (Spring)	17.7–24.8	-	[79]
Cattle slurry (Autumn)	5.9–23.9	-	
Farmyard manure (Spring)	0.4–2.6	-	
Farmyard manure (Autumn)	1.3–1.7	-	
Narrow-band application	8.9–32.0	-	[72]
	-	26	[80]
Cattle slurry (Spring)	7.7–18.9	-	[79]
Cattle slurry (Autumn)	6.4–22.1	-	
Trailing hose	4–28	51	[77]
Railing shoe	4–12	53	[77]
	-	57	[80]
	-	40–50	[75]
Shallow injection	7	76	[77]
	1.5–15.7	-	[72]
	-	73	[80]
	-	40–50	[75]

3.3. Timing of Application

The timing of fertilization is important to avoid nutrient losses. Mineral fertilizer is usually applied at the beginning of the growing season in spring and manure after the first cut [81]. Compared to spring fertilization at the beginning of the growing season, autumn fertilization resulted in higher losses by volatilization, leaching, and denitrification due to more frequent precipitation events and lower N uptake by plants. On the other hand, spring application prolongs the storage time of manure, which can also lead to higher nutrient losses [82]. Based on a study by Smith et al. [83], N losses are up to 43% in September and up to 53% in October. Sørensen and Rubæk [82] found that N is slowly mineralized and nitrified in the period after organic fertilizer application. Therefore, N losses may occur in the period after application. According to He et al. [84], to avoid nutrient losses, organic fertilizer amounts should be divided into smaller amounts, resulting in less nutrient leaching and less N_2O emission.

4. Plant Properties

4.1. Yield

Nutrient availability, especially N, is a limiting factor for plant growth. The DM yield of grass is correlated with the N yield (DM yield = N yield 59.872 − (N yield)^2 × 0.076) and is, therefore, most affected by N application in the form of mineral and organic fertilizers [85].

With the application of cattle manure, the grass yield was between 20% [86] and 56% [87] higher than without fertilization. DM yield was highest in the second year of fertilization [86]. The higher DM yield depends on the availability of nutrients for plant growth, which is provided over time by the mineralization of organic fertilizers [87]. Both aboveground and belowground biomass increased with organic manure application, with aboveground biomass increasing disproportionately with increasing N [88].

In a study by Kacorzyk and Głąb [89], the effect of N application from sheep manure on DM yield was significant, but P and K applications showed only moderate effects. Not only is the total or plant-available content of nutrients important, but the proportions of nutrients, especially an inappropriate N:P ratio in plants, can also limit plant growth. The higher the N:P ratio, the more P was the limiting nutrient, and the lower the N:P ratio, the more N was the limiting nutrient.

The DM yield of grass was also affected by the application technique used to apply manure to the fields. The use of injection techniques significantly increased DM yield as a function of N content in the manure due to a higher efficiency of N conversion to DM [32]. However, the higher the N level, the lower the positive effect of injection application [85].

According to Augustenborg et al. [90], dung excretion during grazing has a positive effect on DM yield, similar to mineral fertilization. The effect of grazing on DM yield depends on the grazing system and intensity. In particular, moderate grazing and rotational systems have a positive effect on biomass build-up, and the yield can be higher, both quantitatively and economically, than when hay or silage is harvested. Important advantages of pasture are the reduced need for additional fertilization, no losses during harvest, storage and transport, and lower costs for machinery [56]. Patches, mainly caused by urine deposition, show increasing concentrations of various nutrients such as N, S, and K in herbage and soil, thus increasing DM yield [91]. Typical nutrient hotspots where patches can develop are in shaded areas and around mineral and water sources [38]. Deposition of excreta led to both increased plant growth and avoidance of grazing [92].

4.2. Quality

As mentioned above, the use of manure as fertilizer has a positive effect on DM yield, although the effect on forage quality is uncertain. While Simić et al. [93] found no significant effect on quality aspects such as better digestibility, Štýbnarová et al. [87] observed a significant increase in crude protein by 9% to 29% depending on the grass species. Crude concentration protein increased with manure fertilization compared to unfertilized grassland. Higher N content improved forage quality by reducing the C:N ratio, resulting in higher availability for digestion and, thus, higher digestibility [38].

According to Rammer and Lingvall [68], manure application affects not only the quality of grass and forbs in terms of nutrient content and digestibility but also the quality of silage. Silage can be contaminated with manure during harvesting after application, especially when surface technology is used. This affects the microbial communities, leading to an increase in bacteria and bacterial activity and favoring the growth of undesirable microorganisms during ensiling.

Grass from pastures tended to be of higher quality than grass silage [56]. Grazing intensity had no significant effect on grass quality, such as lignin, N percentage, or C:N ratio [94]. In a study by Schellberg et al. [50], N uptake from excreta during grazing increased digestibility between 70% and 79% and crude protein content in plants between 10% and 25%. In a rotational grazing system, the nutritional value of plants may decrease due to maturation processes [38].

4.3. Plant Composition and Diversity

Organic fertilization causes changes in plant composition [86]. This increased nutrient availability may favor certain plant species that are more responsive to these nutrients, leading to changes in plant composition and a decrease in plant species diversity [39]. Nitrogen-rich species respond better to organic fertilizers, suppressing and eliminating less competitive nitrogen-poor species, and few of these nitrogen-deficient adapted species can survive. The opposite is true for very nutrient-poor soils. Here, gaps in the vegetative cover can allow undesirable species to spread, especially noncompetitive invasive species. In these areas, intermediate levels of fertilization can contribute to higher plant species diversity [95]. Organic soils also showed lower species richness and a slight positive effect on species richness with increasing fertilization [95].

According to a study by Kacorzyk and Głąb [89], both investigated doses of sheep manure (69 kg N ha^{-1}, 103 kg N ha^{-1}) resulted in a higher proportion of grasses than other plant species such as herbs and legumes. Similar results were found by Knežević et al. [96] that some species, especially grasses, tended to grow faster than other species, such as broadleaf weed species or herbs and legumes such as white clover after fertilization. As a result, grasses became the dominant species while the others declined. The proportion of herbs can be reduced by more than a third within two years. While P and K mainly influence the proportion of herbs, legumes are more affected by applied N. Tampere et al. [97] found that high application rates above 120 kg N ha^{-1} led to the disappearance of white clover. These high N application rates compensated for this loss through higher grass yield but had no significant effect on total yield. According to Kacorzyk and Głąb [89], organic fertilization can lead to an increase in legume percentage as long as the N application rate is lower than 69 kg ha^{-1}. However, the type of application technique had no effect on plant composition [32].

In a study by Socher et al. [39], grazing had a very negative effect on biodiversity in organic soils and a slightly positive effect on less organic soils. It affects plant composition through the release of nutrients through urine or feces [53]. According to Kayser and Isselstein [91], the uneven distribution of nutrients and less grazed areas have created patches where special species can be established. Often, taller plant species can grow here and complement smaller ones [53]. Different patch types under different grazing intensities led to increased biodiversity but with a higher impact under extensive grazing than under intensive grazing [53]. This was due to the preference of cattle for smaller patches, which decreases with increasing LU [53,92].

Table 4 provides an overview of the yield, quality, and plant composition of temperate grasslands depending on manure application.

Table 4. Changes in yield, quality, and plant composition on temperate grassland under different manure applications.

Treatment	Application (kg N ha^{-1} a^{-1})	Yield (t DM ha^{-1})	Quality (g N kg^{-1} DM)	Diversity (Species m^{-2})	Reference
Grazing	336	7.50–8.63	26.1–31.3	-	[41]
Manure application	336	8.17–8.66	22.7–27.2	-	
Sheep manure	103	5.92	-	-	[98]
Sheep grazing	184	5.42	-	-	
Pig slurry	160	±8	-	-	[45]
Pig slurry	320	±14	-	-	
Pig slurry	640	20	-	-	
Cattle slurry	130	±9	-	-	
Cattle slurry	270	±15	-	-	
Cattle slurry	540	19	-	-	
Cattle slurry	300	7.5	-	-	[99]
Poultry manure	300	10.1	-	-	

Table 4. *Cont.*

Treatment	Application (kg N ha^{-1} a^{-1})	Yield (t DM ha^{-1})	Quality (g N kg^{-1} DM)	Diversity (Species m^{-2})	Reference
Cattle slurry conv.	144	11.8	-	22	[48]
Cattle slurry ext.	128	10.5	-	26–28	
Cattle slurry org.	117	10.7	-	>32	
sheep manure	69	3.55/2.15 *	19.78/23.95 *	-	[89]
Sheep manure	103	4.07/2.52 *	19.20/23.32 *	-	
Liquid manure	76–112	8.68	-		[96]
Grazing 1998	220	6.02	36.7	-	[100]
Grazing 1999	220	7.94	34.9	-	
Cut 1998	220	8.81	24.4	-	
Cut 1998	220	8.98	27.8	-	
Untreated cattle slurry	303	0.262 t N ha^{-1}	-	-	[85]
Digested cattle slurry	306	0.270 t N ha^{-1}	-	-	
Cattle slurry, injected	311	0.247 t N ha^{-1}	-	-	
Cattle slurry, surface	303	0.206 t N ha^{-1}	-	-	
Farmyard manure (FYM)	307	0.234 t N ha^{-1}	-	-	
Farmyard manure	n.a.	2.95/1.38 **	-	-	[93]
FYM conventional	280	-	-	12	[101]
FYM organic	140	-	-	16	
Cattle slurry (CS)	202	11.11	-	-	[31]
CS low protein	206	8.78	-	-	
CS composted with hay	183	8.13	-	-	
Cattle FYM	217	9.56	-	-	

* First/second cut. ** First year/second year. n.a.: not available.

5. Soil Chemical Properties

5.1. Soil Carbon (C)

The terrestrial carbon (C) pool, particularly in grassland soils, is one of the most important C sinks on earth [102]. There are several different factors that affect C sequestration in grassland soils, including management practices, the amount of N and other nutrients [103–105], soil physical properties [102], soil organisms [106,107], and environmental factors such as air temperature and water availability. According to Jones et al. [103], manure is an important source of C, although its application can increase dissolved organic carbon (DOC) levels and thus C decomposition rates through the priming effect related to increased respiration. Overall, manure application leads to increased C sequestration despite increased soil respiration due to a positive C balance [29]. C accumulation in the soil results directly from the applied manure and secondarily from increased microbial biomass and higher amounts of plant residues such as litter and roots [108].

Depending on management, grassland can have high CO_2 uptake during the growing season and thus act as a sink for C. The rate of CO_2 uptake can vary from year to year [109]. The type of fertilizer affects soil respiration and, thus, CO_2 emissions. According to a study by Jones et al. [103], the respiration rate is increased by 27% for cattle manure and 41% for poultry manure compared to the control without manure application.

Organic C can be converted to CH_4 by anaerobic digestion [16,110] or emitted directly by livestock [108]. Anaerobic digestion primarily occurs when manure is applied in liquid form, especially on flooded soils or after runoff into surface waters [111]. However, Jones et al. [103] found no direct effect of manure application on CH_4 emissions, except for temporary peaks immediately after cattle manure application. This CH_4 flux originates directly from the manure and is, therefore, largely independent of soil respiration. Only between 0.1% and 0.4% of the total CH_4 emissions originated from soil respiration.

Leaching of DOC is a relatively small but continuous loss and is of great importance for C and GHG balances [112]. Jones et al. [103] found that DOC is continuously increased by manure application. When comparing agricultural manures, DOC increased more after poultry manure application than after cattle manure application. In addition to the type and amount of manure applied, the amount of DOC leached depends on various conditions such as climate and edaphic conditions, e.g., soil structure and texture, pH, and vegetation, especially root distribution and litter quality [113].

Grazing tends to have a positive effect on soil organic carbon (SOC) content due to organic C input via excreta, depending, for example, on landscape position, soil properties, grazing management [114], and climatic factors [115]. Approximately 25% to 40% of C uptake is returned to the soil as excreta [108]. Moderate grazing intensity has the most positive effect on C accumulation, followed by rotational grazing and, finally, high grazing intensity [94]. Depending on management intensity, mowing may result in higher C export compared to grazing, leading to lower C sequestration rates on pastures if C export is not offset by organic fertilizers or other C inputs [116]. However, even under very extensive grazing, C content decreased due to higher rates of SOC decomposition. This was due to low C supply and, thus, depletion of the soil C pool [44]. Paz-Ferreiro et al. [117] suggest that increased nutrient availability, especially N, stimulated soil respiration. Excreta increased CH_4 emissions through deposition effects [116], while emissions decreased over time with aging. According to a study by Voglmeier et al. [118], emissions occurred up to 20 days after deposition. Leaching losses of C as DOC were small compared to emission losses of CO_2 [119]. Jones et al. [116] found in their study that only 2.1% of total C was lost through leaching under grazing management, as grazing primarily increases CO_2 emissions.

Table 5 shows the changes in C storage and C losses as a function of organic fertilizer application on temperate grasslands.

Table 5. Changes in C storages and C losses on temperate grassland with different treatments of fertilization with organic fertilizer.

Treatment	Application (kg N ha^{-1} a^{-1})	C Storage	CO_2 Emissions	CH_4 Emissions	Reference
LCM *, 4 cuts	110	147 g C m^{-2} a^{-1}	1.8 µmol m^{-2} s^{-1}	-	[44]
No fert., 3 cuts	0	−57 g C m^{-2} a^{-1}	3.1 µmol m^{-2} s^{-1}	-	
LCM, 4 cuts	110	64.7–183 t C ha^{-1}	-	-	[120]
No fert., 3 cuts	0	61.0–173 t C ha^{-1}	-	-	
Dairy cow slurry	50	-	-	0.58 kg ha^{-1}	[121]
Pig slurry	50	-	-	0.13 kg ha^{-1}	
Pig slurry	160	0.39 t C ha^{-1} a^{-1}	-	-	[45]
Pig slurry	320	0.28 t C ha^{-1} a^{-1}	-	-	
Pig slurry	640	0.31 t C ha^{-1} a^{-1}	-	-	
Cattle slurry	130	0.43 t C ha^{-1} a^{-1}	-	-	
Cattle slurry	270	0.65 t C ha^{-1} a^{-1}	-	-	
Cattle slurry	540	0.86 t C ha^{-1} a^{-1}	-	-	
Dairy cattle slurry	130–540	-	11. 6–12 t CO_2 eq	-	
Beef cattle slurry	130–540	-	9.1–9.5 t CO_2 eq	-	
Cattle slurry	150/150 **	-	14.03/15.9 t CO_2 C ha^{-1}	1.0/6.4 kg ha^{-1}	[29]
Poultry manure	150/150 **	-	17.22/17.22 t CO_2 C ha^{-1}	0.3/0.7 kg ha^{-1}	
Cattle slurry	150	8.4 t C ha^{-1}	7.49–12.71 t CO_2 C ha^{-1}	0–6.4 kg ha^{-1}	[103]
Poultry manure	150	31.3 t C ha^{-1}	7.0–13.77 t CO_2 C ha^{-1}	−0.1–0.7 kg ha^{-1}	

Table 5. *Cont.*

Treatment	Application (kg N ha^{-1} a^{-1})	C Storage	CO_2 Emissions	CH_4 Emissions	Reference
Cattle slurry conv.	144	-	1.280 t CO_2 eq	5.102 t CO_2 eq	[48]
Cattle slurry ext.	128	-	0.666 t CO_2 eq	4.535 t CO_2 eq	
Cattle slurry org.	117	-	0.428 t CO_2 eq	4.114 t CO_2 eq	
Anaerobic digestate	80.12	-	669.5 mg (kg soil DM)$^{-1}$	-	[122]
Cattle slurry	246.3	-	2030.5 mg (kg soil DM)$^{-1}$	-	
Stockpiled dairy manure	190	154.1 mg C kg^{-1}	733.1 mg C kg^{-1}	-	[123]
Rotted dairy manure	187	186.9 mg C kg^{-1}	796.9 mg C kg^{-1}	-	

* Liquid cattle manure. ** 2002/2003.

5.2. Soil Nitrogen (N)

N is a very important nutrient in the global biogeochemical cycle and is crucial for plant growth and living organisms [38,124,125].

Bittman et al. [126] found that a high proportion of sequestered N comes from microbial N, which can be further increased by manure application. Microbial N is 1.5 to 1.6 times higher at an organic manure application rate of 100 kg N ha^{-1} a^{-1} than at a rate of 50 kg N ha^{-1} a^{-1}.

NH_3 volatilization depends on several factors, such as DM and NH_4^+-N content, manure and soil pH, soil moisture, and available soil C [127]. However, experiments with different DM contents in solid manure and slurry have shown that the DM content of manure has no significant effect on NH_3 emissions [128], while a study by Misselbrook et al. [74] found increasing NH_3 emissions with increasing DM. According to Sun et al. [110], coarse-grained solids slow the penetration of manure into the soil, resulting in increased NH_3 emissions. In addition, higher temperatures and solar radiation led to an increase, while rain and snow events reduced it. However, application to water-filled soils increased NH_3 emissions due to low infiltration rates. Twigg et al. [128] found that about 70% of NH_3 losses occurred in the first eight days after manure application to grassland, while about 90% occurred between the first 32 h and 48 h after application. Overall, about one-third of the total NH_3 is emitted in the first five days.

Manure application increases N_2O fluxes, which are considered to be the main pathway for N losses from grassland soils [129]. The type of manure affects N_2O emissions, e.g., through readily available C and N that stimulate microbial activity. In general, manure application causes the highest N_2O emissions compared to other N_2O sources on grassland [118]. After manure application, NH_4^+ and NO_3^- concentrations increased rapidly due to increased enzyme activity, resulting in increased N_2O emissions [129]. Jahangir et al. [130] found a significant increase in N_2O emissions due to higher denitrification rates after manure application. In their study, the denitrification rate in the A horizon increased from 25% to up to 61%.

N leaching usually occurs in the form of NO_3^- [131], which can be lost as leachate and surface runoff or converted to gaseous form and emitted as THG [130]. The risk of leaching depends on the type of fertilizer, with slurry N being more susceptible to leaching but also more rapidly available for plant uptake compared to solid manure N. This can lead to higher leaching losses, especially outside the main grassland growing season in fall and winter [83].

Pastures tend to have high levels of NO_3^- in the soil. N comes mainly from animal excreta and supplemental manure but also from mineral fertilizers and SOC [130]. During grazing, more than 70% of N uptake is returned to the soil as excreta. Excretion is unevenly distributed. There is usually a high surplus of N at excretion sites. According to a study by Anger et al. [132], between 350 and 1300 kg N ha^{-1} a^{-1} can be excreted on a patch. Plants are not able to take up this amount of N.

Depending on the LU, grazing has a strong effect on N sequestration and mineralization. The higher the LU, the higher the mineralization, and thus, N sequestration also decreases when N input is less than N output [94]. The proportion of NH_3 emissions from grazing was very high, with values between 17% and 37% of the total NH_3 emission losses from livestock [133]. In contrast, Misselbrook et al. [134] estimated that only about 8% of total NH_3 emissions came from cattle grazing. Grazing increased NH_3 emissions, especially on urine patches, due to favorable mineralization conditions such as higher soil moisture and pH on these patches [38]. NH_3 losses can be highly variable. Petersen et al. [135] found a range of 3% to 52% N losses from urine. Higher grazing intensity led to higher NH_3 emissions due to more excretion on the pasture [136]. The same is true for N_2O emissions, as the N content in urine is higher than in feces [118,137].

Table 6 shows changes in N storage and N losses in temperate grasslands as a function of organic fertilizer type, and Table 7 shows these changes as a function of the timing of organic fertilizer application.

Table 6. Changes in N storages and N losses on temperate grassland with different treatments of fertilization with organic fertilizer.

Treatment	Application (kg N ha^{-1} a^{-1})	N Storage(t N ha^{-1})	NH_3 Emissions	N_2O Emissions	N Leaching	Reference
LCM *, 4 cuts	110	6.9–19.4	40–70 kg N ha^{-1}	1.4–1.9 kg N ha^{-1}	0–3.5 kg N ha^{-1}	[120]
No fert., 3 cuts	0	6.6–18.6	-	0.4–0.6 kg N ha^{-1}	0–3.5 kg N ha^{-1}	
Dairy cow slurry	50	-	-	0.34 kg N ha^{-1}	-	[121]
Pig slurry	50	-	-	0.57 kg N ha^{-1}	-	
Pig slurry	640	0.03	-	-	-	[45]
Cattle slurry	130	0.03	-	-	-	
Cattle slurry	270	0.05	-	-	-	
Cattle slurry	540	0.08	-	-	-	
Cattle slurry conv.	144	-	129 kg N ha^{-1}	3.017 t CO_2 eq	-	[48]
Cattle slurry ext.	128	-	113 kg N ha^{-1}	1.808 t CO_2 eq	-	
Cattle slurry org.	117	-	104 kg N ha^{-1}	1.776 t CO_2 eq	-	
Cattle slurry	150	-	-	0.147–0.319 t CO_2 eq	-	[103]
Poultry manure	150	-	-	1.179–6.612 t CO_2 eq	-	
Cattle slurry	150	2.85–2.98	-	↑	10.1–16.2%	[99]
Poultry manure	150	2.81–5.2	-	2200 g N ha^{-1} d^{-1}	1.9–7.0%	
Anaerobic digestate	-	-	-	5.77% of total N	0–4.9%	[122]
Cattle slurry		-	-	8.87% of total N	0.3–17.5%	
Pig FYM		-	1.1–2.8%	0.15–0.3%	-	[79]
Poultry manure	-	-	5.7–10.4%	0.58–2.37%	-	
Pig slurry		-	20.7–24.9%	0.32–1.79%	-	
Grazing dairy cows	120	-	-	1.05–1.07 kg ha^{-1} a^{-1}	-	[118]
Dairy cow slurry	120	-	-	0.47–0.57 kg ha^{-1} a^{-1}	-	
Slurry spreading	250	-	1041/1258 ** kg N farm^{-1}	-	-	[138]
Slurry + grazing	250	-	485/410 ** kg N farm^{-1}	-	-	
FYM	250	-	774/945 ** kg N farm^{-1}	-	-	
FYM + grazing	250	-	485/410 ** kg N farm^{-1}	-	-	

* Liquid cattle manure. ** 150/180 days housed. ↑ Increase of the emissions.

Table 7. Changes in N storages and N losses on temperate grassland at different times of fertilization with organic fertilizer.

Treatment Type of Manure	Treatment Time	Application (kg N ha^{-1} a^{-1})	NH_3 Emissions	N_2O Emissions (kg ha^{-1})	N Leaching	Reference
Urine	In spring	480	-	1.903	-	[137]
	In summer	420	-	5.034	-	
	In autumn	435	-	2.014	-	
Dung	In spring	1020	-	2.035	-	
	In summer	680	-	1.996	-	
	In autumn	720	-	1.538	-	
Dung	In spring	-	5.3%	-	-	[133]
	In summer	-	2.8%	-	-	
	In autumn	-	3.5%	-	-	
Urine	In spring	695	14.9%	-	-	
	In summer	-	9.8%	-	-	
	In autumn	-	8.7%	-	-	
Cattle slurry	April/June 2002	300/170	-	2.5	-	[29]
	April/June 2002	380/150	-	1.2	-	
Poultry manure	2002	150	-	52.1	-	
	2003	150	-	9.3	-	
Slurry						
<4% DM	August–April	-	15%	-	-	[134]
4–8% DM		-	37%	-	-	
>8% DM		-	59%	-	-	
Slurry	May–July	-	60%	-	-	
Solid manure		-	76%	-	-	
Dirty water		-	15%	-	-	
Poultry manure		-	45%	-	-	
Cut	1998	220	-	-	1.7 kg ha^{-1}	[100]
	1999	220	-	-	0.7 kg ha^{-1}	
	2000	-	-	--	12 kg ha^{-1}	
Grazing	1998	220	-	-	1.4 kg ha^{-1}	
	1999	220	-	-	1.1 kg ha^{-1}	
	2000	-	-		46.3 kg ha^{-1}	
Cattle slurry	September	Ø 200	-	-	6.3–26.3%	[83]
	October	Ø 200	-	-	15.5–29.4%	
	November	Ø 200	-	-	10.1–16.2%	
	December	Ø 200	-	-	1.9–7.0%	
	January	Ø 200	-	-	0–4.9%	
Farmyard manure	June	Ø 200	-	-	0.3–17.5%	
	October	Ø 200	-	-	2.9–17.5%	
Cattle slurry	Autumn 2011	24	5.6–14.8%	0.99–1.03	-	[79]
	Spring 2012	67–77	7.7–24.8%	0.72–1.20	-	
	Autumn 2012	71	22.1–23.9%	0.77–1.18	17.0 kg ha^{-1}	
	Spring 2013	77	15.6–18.9%	0.44–0.61	-	
Farmyard manure	Autumn 2011	131	1.3–1.7%	1.28	3.4 kg ha^{-1}	
	Spring 2012	122	0.4–2.6%	0.72–1.28	-	
Dairy slurry control	1998	88.6	0.48 kg ha^{-1}	-	0.19 kg ha^{-1}	[139]
	1999	95.9	0.08 kg ha^{-1}	-	0.016 kg ha^{-1}	
Pig slurry control	2000	59.6	0.05 kg ha^{-1}	-	0.01 kg ha^{-1}	
	2001	113	2.22 kg ha^{-1}	-	0.012 kg ha^{-1}	
Dairy slurry aerated	1998	88.6	0.05 kg ha^{-1}	-	0.02 kg ha^{-1}	
	1999	95.9	0.03 kg ha^{-1}	-	0.018 kg ha^{-1}	
Pig slurry aerated	2000	59.6	0.02 kg ha^{-1}	-	0.009 kg ha^{-1}	
	2001	113	0.05 kg ha^{-1}	-	0.048 kg ha^{-1}	

5.3. Other Soil Nutrients

5.3.1. Phosphorus (P)

Phosphorus (P) is an important element in plant nutrition, as increased P availability leads to better plant growth due to higher N mineralization rates [140]. On grassland farms, P is typically applied as manure, solid manure, or compost [141], increasing the soil P pool.

P can be leached in both dissolved and particulate organic or inorganic form [82]. P losses can especially occur when manure is applied near the surface [142]. However, an unfavorable timing of fertilization—especially before rainfall—or P surplus in the soil can lead to eutrophication of surface waters [131]. At high application rates, especially in coarse-textured soils with many macropores, leaching can be high because P sorption to free sites in the soil matrix is low. In contrast, in fine-textured soils with less macropore flow, the risk of P leaching is lower as long as there is sufficient P sorption capacity [82]. Hahn et al. [142] found in their study that under dry conditions, hydrophobic components in manure reduce the infiltration rate and, therefore, increase the risk of surface runoff when rain starts. On the other hand, as soil saturation increases, the infiltration rate decreases, and more runoff and P losses occur. With increased rainfall or irrigation, there is more colloidal dispersion, which mobilizes a greater amount of particulate-bound P. Over time, the amount of dissolved active P decreases due to increased sorption of P in the soil, manure decomposition, and bioturbation. According to Laurenson and Houlbrooke [143], approximately 6% of applied P is lost to surface runoff in the first seven days after manure application. Over the next two months, runoff losses decreased by 76% due to a reduction in surface dissolved P. Therefore, manure application and other management practices on grasslands need to be optimized to reduce P leaching losses [142]. For example, manure injection and banding, as well as proper timing of application, can reduce soil sealing and thus P loss.

According to several studies, grazing does not seem to have a major effect on P leaching [100,144,145]. In the study by Härdtle et al. [145], P leaching only differed between 0.2 kg P ha^{-1} a^{-1} and 0.4 kg P ha^{-1} a^{-1} without grazing and up to 0.5 kg P ha^{-1} a^{-1} with grazing. Chardon et al. [144] found that 76% of the P was still present in the plots at the end of their study. The low P leaching rate under grazing can be explained by the high sorption capacity of the soil and the low P deposition rates [145].

5.3.2. Potassium (K)

K is an important nutrient for several physiological interactions, such as stomatal regulation [91], and is the second most important nutrient for plants after N. K is of agronomic interest but not of serious environmental concern. In contrast to N and P, it has little effect on groundwater quality, and the EU limit of 12 mg l^{-1} is not yet toxicologically approved [146]. Depending on the management system, surpluses can occur, especially in intensive grassland systems, or deficiencies, mainly in organic and extensive grassland systems [91].

Plant uptake is the main form of K output from the soil system. Due to the high removal of plant biomass and thus high K removal rates, K losses by leaching are low on mowed grassland [91]. Alfaro et al. [147] found that K leaching losses averaged only 6% of total output compared to 88% to 98% by plant uptake. However, according to Kayser and Isselstein [91], due to the high amount of concentrated feed used in intensive dairy farming, there is a high probability of a K surplus when applying the resulting farm manure that cannot be taken up by plants—and therefore a high level of available K leading to increasing losses. The amount of applied K varied between 100 and 130 kg K ha^{-1} a^{-1} on extensively managed and 175 and 250 kg K ha^{-1} a^{-1} on intensively managed (up to four cuts) meadows.

The different types of organic fertilizers had only a small effect on K leaching. According to studies by Kayser and Isselstein [91] and Tampere et al. [97], the application of cattle slurry alone increased K leaching losses from grassland over the years. The type of application and application during or after the growing season had no effect on K leaching.

The most important factor influencing K leaching is the balance between K and N. N fixation influences K uptake by plants and, therefore, K leaching. N application rates had little effect on total K leaching, with a tendency to increase or decrease leaching over the years. The highest leaching losses occurred without N fertilization, depending on the plant composition. An imbalance between N and K can have a negative effect on the ensiling quality of grass [97,146].

On pastures, the amount of K in the soil due to excretion by herbivores can range from 180 kg K ha^{-1} a^{-1} to 500 kg K ha^{-1} a^{-1}, which exceeds plant requirements [91]. According to a study by Kayser et al. [146], about 90% of the total K uptake during grazing was immediately returned to the soil through urine. This resulted in inefficient K recycling and leaching losses. Leaching from urine patches was mainly due to macropore flow and depended mainly on soil surface properties. K leaching from urine patches was highest in summer but only for a few days after application. Kayser et al. [146] suggested that high K leaching in summer is induced by heavy rainfall events.

5.3.3. Calcium (Ca) and Magnesium (Mg)

Ca is an important element for the stability of soil aggregates, particularly by binding clay particles together [148]. Mg is the central element of green plant pigment and helps to regulate water balance [149].

According to a study by Whalen and Chang [150], the amount of Ca and Mg is increased by manure application. However, because anions and acidic compounds bound most of the ions, only a small amount was available for plant uptake, depending on the rate of manure application. Leaching was the main pathway for Ca and Mg losses [91]. The leaching of Ca^{2+} and Mg^{2+} ions is not seen as an environmental problem but as a loss of valuable nutrients [151]. Whenever anions such as nitrates are leached, there are an equal number of cations that act as counterions. In particular, Ca and Mg are counterions of nitrate. Therefore, Ca and Mg are leached in addition to nitrate and other anions [91].

Di and Cameron [151] estimated that 60% to 99% of Ca^{2+} and Mg^{2+} ions ingested during grazing are returned by excretion. In their study, leaching losses of Ca^{2+} were determined to be 213 kg Ca ha^{-1} a^{-1} and 17 kg Mg ha^{-1} a^{-1} of Mg^{2+}. Most of these leaching losses occurred on urine patches.

Table 8 shows the losses of P, K, Ca, and Mg from different manure applications in temperate grassland.

Table 8. Losses of P and K from temperate grassland under different manure applications.

Treatment	Manure Type	Application Amount	Special Technique	P	K	Reference
Grazing 1999	-	-	No drainage	-	5 kg ha^{-1} a^{-1}	[152]
Grazing 2000	-	-	No drainage	-	13 kg ha^{-1} a^{-1}	
Grazing 1999	-	-	Drainage	-	5 kg ha^{-1} a^{-1}	
Grazing 2000	-	-	Drainage	-	9 kg ha^{-1} a^{-1}	
Fertilization 1999	Cattle FYM	122 kg K ha^{-1}	No drainage	-	19 kg ha^{-1} a^{-1}	
Fertilization 2000	Cattle FYM	304 kg K ha^{-1}	No drainage	-	31 kg ha^{-1} a^{-1}	
Fertilization 1999	Cattle FYM	122 kg K ha^{-1}	Drainage	-	7 kg ha^{-1} a^{-1}	
Fertilization 2000	Cattle FYM	304 kg K ha^{-1}	Drainage	-	23 kg ha^{-1} a^{-1}	
Intensive	Cattle slurry	34.6 kg P ha^{-1}	-	5.3 kg ha^{-1}	-	[48]
Extensive	Cattle slurry	30.9 kg P ha^{-1}	-	4.5 kg ha^{-1}	-	
Organic	Cattle slurry	23.2 kg P ha^{-1}	-	−2.3 kg ha^{-1}	-	
Fertilization on medium-P site	Dairy manure	-	1 d sprinkler	3.72 mg L^{-1}	-	[142]
		-	1 d watering can	1.17 mg L^{-1}	-	
		-	8 d sprinkler	0.95–2.09 mg L^{-1}	-	
		-	8 d watering can	0.84–0.90 mg L^{-1}	-	
Fertilization on high-P site	Dairy manure	-	1 d sprinkler	0.75–1.93 mg L^{-1}	-	
		-	1 d watering can	2.17–2.31 mg L^{-1}	-	
		-	8 d sprinkler	2.04–5.25 mg L^{-1}	-	
		-	8 d watering can	1.20–1.40 mg L^{-1}	-	

Table 8. *Cont.*

Treatment	Manure Type	Application Amount	Special Technique	P	K	Reference
Fertilization	Cattle slurry	425 kg K ha^{-1} a^{-1}	-	-	149 kg ha^{-1}	[146]
Grass-clover sward	.	166 kg K ha^{-1} a^{-1}	-	-	89 kg ha^{-1}	
Application in summer	Cattle urine	60 g K m^{-2}	-	-	2.4–4.2 g m^{-2}	
Application in Autumn	Cattle urine	74 g K m^{-2}	-	-	4.7–7.1 g m^{-2}	
Cut 3 times	Dairy manure	14.5 kg P	Grass cover	14 g ha^{-1}	-	[100]
Grazing	Dairy manure	14.5 kg P	Grass cover	11 g ha^{-1}	-	
1998	Dairy manure	6.4 g P, 21.4 g K DM^{-1}	Fertilization without aeration	1.50 kg ha^{-1}	5.96 kg ha^{-1}	[139]
1999	Dairy manure	11.2 g P, 53.6 g K DM^{-1}		0.06 kg ha^{-1}	0.62 kg ha^{-1}	
2000	Dairy manure	12.5 g P, 16.5 g K DM^{-1}		0.06 kg ha^{-1}	0.22 kg ha^{-1}	
2001	Swine manure	-		0.89 kg ha^{-1}	5.32 kg ha^{-1}	
1998	Dairy manure	6.4 g P, 21.4 g K DM^{-1}	Fertilization with aeration	1.13 kg ha^{-1}	0.72 kg ha^{-1}	
1999	Dairy manure	11.2 g P, 53.6 g K DM^{-1}		0.06 kg ha^{-1}	0.27 kg ha^{-1}	
2000	Dairy manure	12.5 g P, 16.5 g K DM^{-1}		0.02 kg ha^{-1}	0.13 kg ha^{-1}	
2001	Swine manure	-		n.a.	1.17 kg ha^{-1}	

n.a.: not available.

5.4. Soil pH Value

Soil pH is a major driver of several transformations in soils. Changing pH can affect the chemical form of nutrients [38]. Manure contains a certain amount of 0.3 to 110.7 g/kg Ca^{2+} and 0.1 to 11.5 g/kg Mg^{2+}, depending on the origin of the manure [153]. According to the study by Naramabuye and Haynes [153], poultry manure contained the highest amount of Ca^{2+} and Mg^{2+} ions, followed by pig and cattle manure. Therefore, manure application has a long-term effect on increasing the pH of grassland soils due to the presence of Ca^{2+} and Mg^{2+} [12,153] and the oxidation of organic anions during manure decomposition, resulting in a higher buffering capacity [12]. In addition to Ca^{2+} and Mg^{2+} ions, other carbonates, bicarbonates, and organic acids with carboxyl and hydroxyl groups present in manure also affect buffering capacity [154]. Decomposition processes produce organic anions in the form of phenolic material that can bind protons from the soil and thus increase the soil pH of grassland soils [153].

Acidification of manure, where the addition of acid lowers the pH of the manure, is increasingly being used to reduce GHG and NH_3 emissions from manure. The typical pH was below six when H_2SO_4 was used and below five when lactic or hydrochloric acid was used. The altered conditions and effects of reduced pH should be considered in the subsequent availability of nutrients [155].

5.5. Soil Bulk Density

Bulk density affects several soil parameters important for crop production, including hydraulic conductivity, gas diffusion, nutrient uptake, and root growth [156,157]. According to a study by Miller et al. [156], bulk density is positively affected by manure application due to increasing SOC content, which is associated with decreasing bulk density.

According to Mestdagh et al. [158], grazed soils tended to have lower bulk densities than mowed grassland soils. In their study, SOC content was 6% to 7% higher under grazing than under mowing. However, a change in soil bulk density can be explained not only by a change in SOC but also by mechanization or trampling [158,159]. According to Pietola et al. [159], trampling can increase soil bulk density. This can alter the positive effect of higher SOC content [158].

5.6. Soil Porosity

Soil porosity is mostly based on the soil type, organic matter, decomposition, mineralization processes [160], and tillage [161].

Manure application and, thus, increasing SOC content also changes the pore size distribution [161,162]. Kirchmann and Gerzabek [162] found a general increase with manure application. In particular, the proportion of fine macropores between 60 and 600 μm increased rapidly.

Although grazing increases SOC content [158], it can lead to a decrease in porosity due to clogging of surface pores and increased compaction [159,163]. The authors found a decrease in pores >30 μm from 11.2% to 9.5% by trampling. Since Greenwood et al. [164] found an increase in soil porosity years after cessation of grazing, the negative effect of trampling and the positive effect of wetting and drying cycles were much greater than the effect of animal excreta during grazing.

5.7. Soil Hydraulic Properties

According to Dlapa et al. [161], manure application to grassland soils increased water retention due to increasing SOC content. The authors found in their study that SOC content had an even stronger effect on water retention than texture and clay content, as coarse soil with high SOC content had higher water retention than fine-textured soil with low SOC content.

Near-saturated soil hydraulic conductivity is also increased in grassland soils after manure application due to increased biological activity [163]. The increased biological activity, e.g., by earthworms [165], resulted in more continuous and less tortuous pores, which allowed better water flow [163].

Grazing can reduce soil water conductivity—especially near saturation conductivity—due to partial compaction and clogged surface pores [163]. This resulted in an 85% to 90% reduction in water infiltration on clay soils [159]. Greenwood et al. [164] found a significant improvement in soil physical properties after excluding grazing due to the elimination of soil compaction by animals. For example, pasture soils without grazing had higher unsaturated hydraulic conductivity than pasture soils with grazing. When grazing was stopped, they could not find significant differences between the pasture that had not been grazed for 2.5 years and the pasture that had not been grazed for 27 years. Thus, the improvement processes seemed to occur very quickly after the cessation of grazing.

5.8. Size of Soil Aggregates

Organic manure application increases the proportion of aggregates in grassland soils. Linsler et al. [166] found a higher proportion of aggregates in soils with manure application compared to plots without manure application. The concentration of smaller aggregates tended to decrease after manure application. This was due to the formation of larger aggregates from smaller aggregates with the binding or cementing agents from the organic fertilizer [167]. The amino sugars of soil microbial communities, especially bacteria, serve as binding agents. They bind soil primary particles to form microaggregates, which are then bound together to form macroaggregates. These aggregates serve as niches for the microbial communities, providing them with better growth conditions. This was a positive feedback loop [168]. According to Wortmann and Shapiro [169], the formation of macroaggregates depends on the organic fertilizer applied. Feedlot solid manure and compost stimulated the formation of large macroaggregates >2 mm by 200% and more compared to control plots with no application. The effect of compost was about 240% greater than that of manure.

Manure application also leads to higher water stability of aggregates. The hydrophobic organic compounds are thought to be the cause of the improvement in water stability. Aggregate stability is higher in irrigated soils than in dryland plots due to higher soil moisture content [150].

Soil aggregation due to manure application also results in less runoff and, therefore, less P loss, which was observed two weeks after application. This effect persisted for more than one year [169].

During grazing, SOC content increased, resulting in increased formation and stability of large aggregates >2 mm and small aggregates <0.5 mm [170]. The author found that these effects occurred only at grazing intensities of 0.8 LU ha^{-1}. Higher intensities of 1.8 LU ha^{-1}

and 3.4 LU ha^{-1}, respectively, resulted in higher rates of organic C decomposition and, thus, larger aggregates.

6. Soil Biological Properties

6.1. Soil Organisms

In grassland soils, microbial biomass accounts for about 45% of the humic fraction and is mainly favored by the high C content of grassland soils [106]. Due to the high content of labile forms of C, manure application has a positive effect on microbes [126], depending on the type of manure [61]. While SOC changes slowly, soil microbial biomass often develops rapidly after the application of organic amendments [171]. In particular, the application of manure together with straw stimulates fungal activity [31].

The C content of manure [171], with SOC content [172], is the most important factor for the growth of microbial populations, turnover rates, and microbial mortality rates, in addition to climatic conditions. However, Neufeld et al. [173] did not find significant differences in soil microbial growth between different forms of manure application—liquid or solid—despite different SOC content. However, in a study by Bittman et al. [174], manure application over several years, especially dairy manure, increased overall microbial biomass, especially fungal biomass. Bacterial biomass decreased over the years because common soil bacteria such as *Pseudomonas* spp. had better growth conditions on the labile organic substrates in the manure, while fungi grew faster on recalcitrant substrates such as lignin. Zhelezova et al. [175] showed the effects of manure application depending on the applied manure and soil type. Here, the number of fungi in poultry and pig manure was twice as high as in cattle manure. In addition, microbial populations changed over time depending on soil type. Because the microbial communities were rapidly activated in Chernozem, there was little change in taxonomy. In contrast, in Retisol, the microorganisms were only slightly activated in the first few months, but taxonomy changed significantly over time. Overall, a large number of manure-derived microorganisms survived in the soil. A similar result was found by Sayre et al. [176]. While the population of manure-derived microorganisms in the soil increased, the population of other microorganisms decreased. On some plots, there was a complete change after two years. In contrast, in the study by Semenov et al. [177], most of the manure-derived bacteria in the soil died within nine weeks. At the same time, the soil microbiota was mainly activated by manure application.

According to Conant et al. [178], mechanisms such as microbial immobilization, formation of recalcitrant litter, and small or inactive microbial populations can limit N mineralization. As N levels increase, these mechanisms are prevented, and N mineralization is accelerated. Soil N is directly related to soil C. Therefore, changes in C result in changes in N. A study by Laughlin et al. [179] showed that at high C levels induced by manure application, fungi tended to become dominant. They were the most important actor for N transformation, especially under permanent grassland, and therefore the dominant species for N_2O emissions. According to a study by Vries et al. [180], high fungal biomass reduced N losses due to higher N uptake by plants and N immobilization. Simpson et al. [106] found that more than 80% of organic N comes from microbial sources. While microbes require N to grow, they immobilized soil N when there was insufficient soluble N available. This occurred in cycles as microbes died and decayed over time, while N was released and returned to the soil [38]. Therefore, microbes were considered a labile pool of plant nutrients with a turnover time of one to three years [171]. Due to high C:N ratios in decomposing organic matter, N immobilization outweighs N mobilization in grassland soils [52]. Microbial growth was more influenced by nutrient availability, especially N, than by energy substrates [181].

Hu et al. [182] found that 60% of the total microorganisms under pastures were bacteria. The number of Gram-negative bacteria was twice that of Gram-positive bacteria. On the other hand, according to a study by Semenov et al. [177], fog Gram-negative bacteria died in the soil. The majority of surviving bacteria were Gram-positive. According to Mencel et al. [183], the mass of bacteria in pastures decreased with soil depth. Due to decreasing organic matter and nitrogen, the number of Gram-positive bacteria decreased in particular. While the number of bacteria decreased with depth, actinobacteria are stable up to 30 cm depth. Soils from extensive or lightly grazed pastures had higher bacterial content than intensively grazed systems. Since grazing intensity changes the plant species composition, the bacterial population and diversity also change. Hu et al. [182] found that fungal populations, like bacteria, decreased under high grazing intensity and with soil depth. In addition, fungi were higher in total number and relative to bacteria under light grazing. However, according to Musiał, Kryszak, Grzebisz, Wolna-Maruwka, and Łukowiak [184], the increase in fungal population was five times higher after mowing than after grazing.

6.2. Changes in Microbial and Enzyme Activity after Manure Application

Enzymatic activities depend on various factors such as soil texture and moisture, substrate, temperature, and humic substances [185]. Nevertheless, manure application had a direct effect on microbial and enzyme activity in grassland soils [173], independent of other factors such as climatic conditions or soil properties [24]. Enzyme activity is essential for nutrient recycling in grassland soils, especially for N and P [186]. Dong et al. [187] showed the importance of the form of added N for enzyme activities. In organic treatments, the phenol oxidase and peroxidase had 19% and 43%, respectively, the highest increase of all treatments. N-acquiring enzymes were stimulated regardless of the form of fertilization. Based on a study by Neufeld et al. [173], the type of manure had no significant effect on microbial and enzyme activity. However, each type of manure application had a positive effect on microbial activity, although the liquid and solid manures had different levels of C and N. Enzymes were not directly bound to living microbes, as they could bind to organic and clay particles and remain active [173].

According to Mencel et al. [183], enzyme activities are higher under pastures. Due to animal excretion, the SOM and different macro- and microelements increased. This increased the number and activity of different microorganisms. A higher botanical composition in pastures led to a higher composition of bacteria species, inhibiting the roots from specific enzymatic reactions, which accumulated in the soil.

Table 9 provides an overview of the effects of different manure applications on microbial activity and growth in temperate grassland soils.

Table 9. Impact of different manure applications on microbial activity and growth in temperate grassland soils.

Treatment	Nutrients	Impact on Microbes	Impact on Bacteria	Impact on Fungi	Reference
Addition of organic nutrients by rabbit grazing	-	↑	↑ not significant	↕	[188]
Green manure application	2052 C/65 N (kg ha^{-1})	↑	34.3 nmol g $soil^{-1}$	1.8 nmol g $soil^{-1}$	[189]
Manure application	2212 C/104 N (kg ha^{-1})	↑	36.8 nmol g $soil^{-1}$	1.3 nmol g $soil^{-1}$	
Sawdust application + $Ca(NO_3)_2$	2054 C/81 N (kg ha^{-1})	↑	37.4 nmol g $soil^{-1}$	1.7 nmol g $soil^{-1}$	
Manure application	20 t ha^{-1} 54.4 C/4.49 N (mg g $soil^{-1}$)	↑	-	-	[190]
Manure application	400 C/59 N (kg ha^{-1})	↑	-	-	[172]
Acetate as C source (replacement for manure)	2.5 mL as solution	↑	↓	↑	[179]
Stockpiled dairy manure	100 t ha^{-1}	↑	-	-	[123]
Rotted dairy manure	100 t ha^{-1}	Slightly higher ↑	-	-	

Table 9. *Cont.*

Treatment	Nutrients	Impact on Microbes	Impact on Bacteria	Impact on Fungi	Reference
Cattle slurry	3361 OM/98 N (kg ha^{-1})	↑	56 µg C g dry soil^{-1}	15 µg C g dry soil^{-1}	[31]
Cattle slurry low protein	3718 OM/104 N (kg ha^{-1})	↑	57 µg C g dry soil^{-1}	14 µg C g dry soil^{-1}	
Cattle slurry composted with hay	4161 OM/170 N (kg ha^{-1})	↑	53 µg C g dry soil^{-1}	16 µg C g dry soil^{-1}	
Cattle FYM	6347 OM/171 N (kg ha^{-1})	↑	52 µg C g dry soil^{-1}	17 µg C g dry soil^{-1}	

↑ Increase, ↓ Decrease, ↕ Increase and decrease.

7. Summary and Conclusions

Temperate grasslands—mostly of anthropogenic origin—are used for meadows, pastures, or mown pastures. Different management practices (intensity, organic versus conventional farming, fertilization techniques, and timing) and the application of organic fertilizers—especially manure—have a strong influence on several grassland characteristics (e.g., forage yield and quality) and on several soil properties, including chemical, physical and biological properties. Fertilization with organic fertilizers is a common practice in grassland management to increase nutrients for optimal plant growth and to increase SOC content to improve soil properties. Fertilization is essential to maintain grassland fertility. Only with high fertility, achieved through fertilization, is it possible to produce high yields of good forage quality from grassland. Manure replenishes nutrient content and improves soil fertility by increasing nutrient storage, pH, physical conditions for water infiltration and root growth, and microbial activity. There is an effect on soil chemical properties such as C and N storage and the content of other nutrients, in this case, P, K, Ca, and Mg. Soil physical properties are improved by manure application. Bulk density is reduced, and porosity and hydraulic conductivity are improved. In addition, larger soil aggregates are formed, and aggregate stability is increased. Biological properties also increase, especially microbial biomass and microbial and enzyme activity.

However, additional factors must be considered when evaluating the impact of organic fertilizers on forage yield and quality. In particular, light and water have a major impact on nutrient yield and value. When water is limited, aboveground biomass does not respond to nutrient application, while when light is limited, belowground biomass response to N is limited.

On the other hand, manure can create a nutrient surplus beyond plant needs and increase losses through greenhouse gas emissions or leaching. The lost nutrients are not only economically lost from the nutrient cycle of the farm, but they can also cause environmental damage. Nutrient losses can be prevented or minimized by using advanced application techniques, such as injection technology, and by applying at times when crops have high nutrient needs and not exceeding nutrient requirements.

Optimizing the use of organic fertilizers by applying the 4R principles of ‘right source’, ‘right rate’, ‘right time’, and ‘right place’ is the best way to improve economic conditions and reduce GHG emissions and leaching [191].

The effects of organic fertilization on temperate grasslands and the advantages over mineral fertilization are more or less well understood, but there is still a lack of widespread implementation in common agricultural practice and acceptance by farmers and society.

8. Recommendation

For sustainable agriculture, it is important to close nutrient cycles and use resources efficiently. Organic manures and animal excreta are valuable nutrient resources and can replace mineral fertilizers. This review provides an overview of their effects on grassland properties and some ideas for their sustainable use:

1. The use of organic fertilizers should be given priority over the use of mineral fertilizers, in accordance with legal requirements, so as not to double the burden on the environment.
2. Mineral fertilizers should be used only when necessary and as an additional source of nutrients.
3. Manure should be used in a way that maximizes its usefulness as a valuable fertilizer and minimizes its negative impact on the environment.
4. Manure fertilization should be based on up-to-date data on the amount and composition of all relevant nutrients, especially nitrogen and phosphorus.
5. To avoid over-fertilization and the loss of valuable nutrients through leaching or greenhouse gas emissions, soil status should be known, at least for nitrogen and phosphorus.
6. Fertilization planning should be based on soil data and long-term yield data, which determine the actual nutrient demand of plants.
7. Organic fertilizers should be applied only during the growing season when plants have high nutrient requirements.
8. Nutrient losses due to leaching and greenhouse gas emissions must be avoided by using appropriate application techniques, such as broad band spreaders or injection techniques.
9. Organic fertilizers should be used instead of mineral fertilizers to increase carbon inputs and thus improve many soil parameters, which at the same time increases soil fertility and resilience to climate change impacts such as droughts or heavy rainfall.
10. Organic fertilizers should be applied in a manner and at a rate that promotes active soil life.
11. Livestock densities should be adapted so that the positive effects of excreta on soil and plant parameters and their diversity are not negated by trampling and increased biomass decomposition.
12. Knowledge transfer between scientists, policy makers, and farmers should be intensified at local, national, and global levels.

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