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A Holistic Agronomic Assessment of Slurry Application Methods in Grassland: Implications of Distribution Equipment, Consistency and Timing for Forage Production

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ABSTRACT

The use of low ammonia emission equipment for slurry distribution has become mandatory in a number of countries. However, the effects of different application methods on dry matter (DM) yield, nitrogen (N) utilisation, botanical composition and forage quality are still debated. This study offers a comprehensive assessment of the effect of various slurry application methods on forage production. Slurry distribution equipment (broadcast; band-spread; trailing-shoe), as well as slurry consistency (unaltered or extra dilution), timing (immediately or delayed after preceding cut) and sward types (with or without legumes) were tested at two sites. Low-emission equipment significantly increased DM yield and N utilisation at one of the two sites. Slurry dilution proved positive for N utilisation and DM yield, while early application timing had marginal effects. Low-emission equipment had no effect on the proportion of legume species, and at one site, it had only irrelevant effects on the proportion of undesired species. Silage quality was not negatively affected by low-emission equipment but was indicated to be positively influenced by extra diluted slurry and early application. We conclude that the use of low-emission slurry distribution equipment can be advantageous in intensively managed grasslands in terms of N utilisation and yield. However, these positive effects are not guaranteed. Negative effects on forage quality are very unlikely with such equipment, provided that the general recommendations for silage production are followed. Slurry dilution is also advantageous, particularly when broadcast or band-spread equipment is used.

1 | Introduction

An increasing number of countries are addressing the need to reduce ammonia (NH_3) emissions from agriculture through concerted restrictions linked to the management of liquid and solid manure. In Switzerland, for example, a country-wide obligation to use distribution equipment reducing ammonia emissions (low-emission equipment), such as band-spread, trailing-shoe or injection equipment for distribution of liquid manure (henceforth referred to as slurry), started in 2024 (LRV 2024). Broadcast equipment such as splash-plate is now only allowed in special situations (e.g., difficult topography). Furthermore, the requirement to reduce ammonia emissions and other negative environmental impacts by fertilisers containing nitrogen (N) is addressed by increasingly restricting the amount of applied fertiliser in all member countries of the

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European Union (e.g., Directive 2008/50/EC). Thus, optimal N utilisation of fertilisers, particularly liquid and solid manure, needs to be improved (Stark and Richards 2008).

Low-emission slurry distribution equipment is assumed to enhance N uptake by plants, both due to reduced ammonia emissions and due to better soil infiltration, as slurry is deposited in strips close to the soil surface or injected into the soil (Rodhe 2003; Sommer et al. 2006; Bhandral et al. 2009). Pedersen et al. (2021) estimated the exposed surface area covered with slurry to be ~50% after broadcast application, ~35% after band-spreading and ~20% after injection. Moreover, less ammonia may be emitted when slurry is deposited with low-emission equipment under the canopy of a regrown sward (compared with application onto stubbles) due to the shading of the slurry bands (Misselbrook et al. 2002; Thorman et al. 2008). Compared with broadcast distribution, the combination of all these effects reduces ammonia emissions by 26%–51%, 24%–65% and 31%–78% for band-spread, trailing-shoe and injection equipment, respectively (averages of experiments reported in Rubæk et al. 1996; Smith et al. 2000; Misselbrook et al. 2002; Bourdin et al. 2014; Häni et al. 2016; Huijsmans et al. 2016; Maris et al. 2021). The highly variable results for each type of equipment can be explained by differences in application rate, slurry dilution, soil water status, irrigation and meteorological conditions (Mkhabela et al. 2009). As a higher proportion of total ammoniacal N (TAN) in the applied slurry enters the soil due to the reduced ammonia emissions, N uptake and therefore N use efficiency are expected to be improved (Hoekstra et al. 2010).

A key factor affecting ammonia emissions and N use efficiency is the consistency of the applied slurry (Mkhabela et al. 2009). Viscous slurry, which is usually associated with a higher dry matter (DM) content, is less easily washed from plants by rain (Rodhe 2003), and infiltrates less rapidly into the soil than free-flowing slurry (Sommer et al. 2006). The quicker the slurry infiltrates into the soil, the less prone it is to ammonia loss (Bhandral et al. 2009). In the context of distribution equipment, slurry consistency can strongly affect ammonia reduction and applicability. For broadcast distribution, the use of free-flowing slurry is important for reduced emissions and slurry residues in the harvested forage, while slurry consistency may be less critical for trailing-shoe and injection equipment (Øyen et al. 1995; Rubæk et al. 1996). However, studies on the interactions between distribution equipment and slurry consistency are rare.

The ideal timing for slurry application following mowing may not be the same for all types of distribution equipment. While an application shortly after mowing could be best for broadcast distribution to avoid slurry residues at harvest (Coblentz et al. 2014), slurry can be applied by low-emission equipment in a regrown sward without soiling the forage (Laws et al. 2002). However, a delayed application could damage the sward if the regrown canopy has become too tall, particularly when using injection equipment (Wightman et al. 1997; Lalor et al. 2013). Moreover, slurry application by low-emission equipment beneath the canopy into a regrown sward can reduce ammonia emissions due to shading and/or reduced air flow on the applied slurry (Sommer and Olesen 2000). By contrast, application soon after mowing could allow the plants to benefit longer from the applied TAN until the following cut. Ideal timing in terms of N utilisation therefore remains debated.

An increase of N available to plants by low-emission equipment, free-flowing slurry or optimised timing following mowing should have an impact on N uptake and, consequently, on DM yield. The results of previous studies in grassland are, however, not conclusive, showing either positive results (Øyen et al. 1995; Rubæk et al. 1996; Lorenz and Steffens 1997; Bittman et al. 1999; Laws et al. 2002; Carter et al. 2010; Hoekstra et al. 2010; Lalor et al. 2011) or indifferent effects on N uptake or DM yield (Misselbrook et al. 1996; Kayser et al. 2015; Seidel et al. 2017), and sometimes even negative effects for injection equipment (Misselbrook et al. 1996; Maris et al. 2021).

It has been suggested that the additional N available to plants in the context of the N economy of intensively managed grass-clover grasslands could be too small for consistent effects on yield to be expected (Huguenin-Elie et al. 2018). Legume proportion and N input through symbiotic N fixation can be reduced by increased N availability from slurry applications (Nyfeler et al. 2009, 2011), the former counteracting the latter. Other suggestions state that the sward can be damaged by slurry application: Botanical composition can be negatively affected by mechanical damage, scorching or smothering (Wightman et al. 1997; Chen et al. 2001; Laws et al. 2002; Lalor et al. 2013). Gaps arising from sward damage can be invaded by undesired species (Haggar 1971; Parish 1987; Prins and Snijders 1987; Barthram et al. 2005; Amiaud et al. 2008). However, knowledge of the effects of slurry application methods on botanical composition is scarce (e.g., Christie 1987; Anderson and Christie 1995; Liu et al. 2010).

Another major discussion point in the context of the use of low-emission equipment is the effect on forage quality: More slurry residues might end up in the harvested plant material after band-spread application, as dried slurry bands can be lifted up by the growing plants, or soil residues might be produced by soil disturbance. Such effects have been reported by Laws et al. (2002) and Dale et al. (2012). Both mechanisms would increase the occurrence of non-forage material, detrimental bacteria and straw residues. Among the detrimental bacteria, butyric acid-producing bacteria (*Clostridium tyrobutyricum* L.) are particularly problematic, as they not only increase the content of butyric acid in the silage but are also responsible for cheese bloating (Rammer 1996; Rammer et al. 1997; Vissers et al. 2007; Coblentz et al. 2014). However, the effect of the distribution equipment on forage contamination may strongly depend upon the type of slurry (viscous vs. free-flowing, Rodhe 2003) and/or the timing of application (Davies et al. 1996): a delayed application by low-emission equipment into a regrown canopy could minimise such detrimental effects, while late application by broadcast equipment has been well-documented to be detrimental to hygienic forage quality (Dorn-In et al. 2025). However, the combined effects of equipment, slurry consistency and timing have not yet been determined.

The aim of the experiment reported herein was to evaluate the combined effects of slurry distribution equipment, slurry consistency and application timing following mowing on (i) Grassland

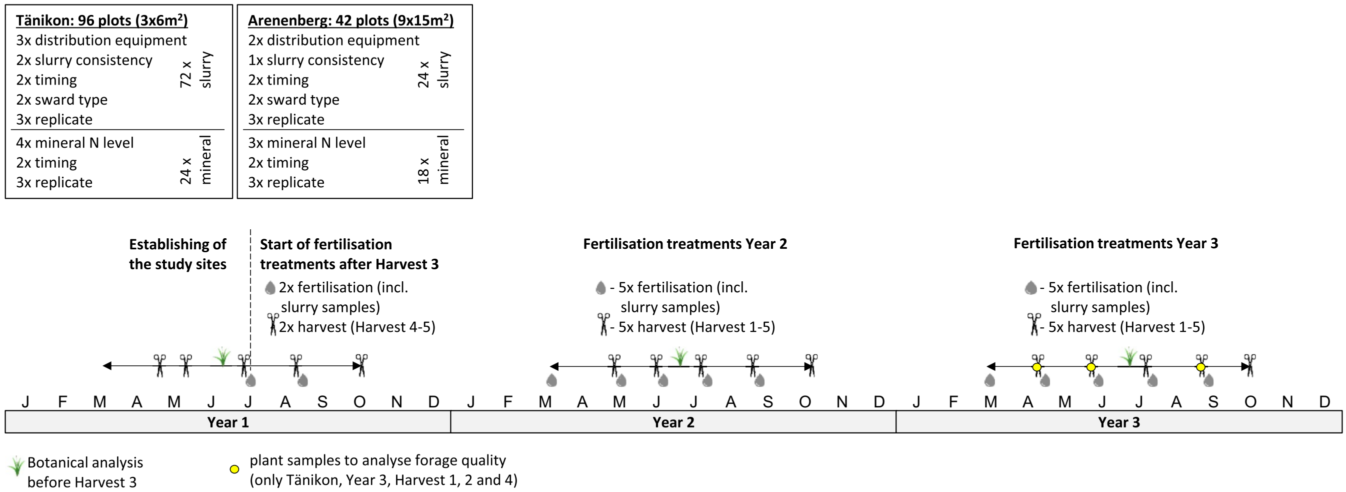

FIGURE 1 | Overview of the experimental design and field management at Tänikon and Arenenberg during the 3 years of the study.

yields, mineral fertiliser equivalence and apparent N recovery, (ii) Botanical composition, and (iii) Forage quality.

2 | Material and Methods

2.1 | Study Sites

The field experiment was carried out on intensively managed, sown grasslands at two sites of the Swiss Plateau for 3 years (2012–2014). At the first site, Tänikon (47.481945°N, 8.906243°E, 535 m a.s.l.), the soil was a clayey loam (see Table S5 for soil characteristics). The annual temperature was 9.6°C, and the annual precipitation was 1137 mm, on average across 2011–2021. At the second site, Arenenberg (47.66729°N, 9.06810°E, 473 m a.s.l.), the soil was a sandy loam, with an average annual temperature of 10.7°C and annual precipitation of 776 mm. The grasslands were grass-clover mixtures sown in 2008 (or 2010 for two blocks at Arenenberg). See experimental design Figure 1 for more details and Table S2c,d for botanical composition. Additionally, legume-free plots (hereinafter L_0) were created at both sites by applying herbicides against dicotyledonous plants and overseeding *Lolium perenne* L. after the first cut of 2012.

2.2 | Experimental Design

The following factors were tested in this experiment (Figure 1): (i) slurry distribution equipment (broadcast (BC), band-spread (BS), trailing-shoe (TS)), (ii) slurry consistency (unaltered slurry, slurry with extra dilution), (iii) timing of application (early: 1–3 days after the preceding cutting, late: 7–10 days afterwards) and (iv) sward type (swards with and without legumes, henceforth named L_+ and L_0, respectively). Unaltered slurry had an average DM content of 4.1%, as retrieved from the farm, and slurry with extra dilution had an average DM content of 2.4%. In addition, supplemental L_0 plots were integrated to add different levels of mineral N fertiliser application to the experiment.

At Tänikon, the full factorial experiment tested all levels of all factors and was arranged in a completely randomised design with three replicates (3 equipment types × 2 consistencies × 2 timings × 2 sward types × 3 replicates = 72 plots). The mineral N fertiliser series integrated into the randomised design included 4 N levels (0, 15, 30 and 60 kg N ha^{-1} year^{-1}) and two application timings (4 N levels × 2 timings × 3 replicates = 24 plots). For this site, an experimental slurry tanker was previously constructed, allowing precise slurry application on small plots (3 × 6 m^2 each).

At Arenenberg, the experiment tested two slurry distribution equipment types (BC and BS), the two application timings (early and late) and the two sward types (L_+ and L_0) (Figure 1). As at Tänikon, supplemental L_0 plots to test mineral N fertiliser equivalent were integrated with the two application timings, but the series included only three N levels (0, 36 and 72 kg N ha^{-1} yr.$^{-1}$). Slurry consistency was the same for all treatments (unaltered dilution with 3.2% DM content, on average, across all fertilisation events). The plots were arranged in a randomised complete block design with three replicates (2 equipment types × 2 timings × 2 sward types × 3 replicates = 24 plots with slurry application, and 18 plots with mineral N application). In this case, the experiment was carried out with farm facilities demanding a larger plot size (9 × 15 m^2 each). The experiment should be conducted on already established grassland, as destroying the existing plant cover and preparing the soil for sowing could significantly alter the nitrogen dynamics in the soil. As the main plot with established grassland available at Arenenberg was not large enough, an adjoining plot with a very similar grass-clover mixture was included. Indeed, for both mixtures, the main species were *Trifolium repens* L., *Trifolium pratense* L., *Lolium perenne* L., *Dactylis glomerata* L. and *Phleum pratense* L.; minor species were *Poa pratensis* L. and *Festuca rubra* L. in one mixture and *Festuca pratensis* Huds. in the second one. The first mixture was used for two replicates and the second mixture for the third replicate.

2.3 | Slurry and Mineral Fertiliser Applications

The experimental slurry tanker facility at Tänikon was equipped with an installation to switch between BC (splash-plate), BS (hoses at 5–6 cm height with 30 cm interspace) and TS (shoes at 25 cm interspace). The farm equipment at Arenenberg allowed a switch between BC (gooseneck-distributor) and BS (hoses with 30 cm interspace and at 0–10 cm height with closer ground contact in the middle and a larger distance to the border).

At both sites, the entire experimental field was fertilized at the same application rate. In Year 1, fertiliser application was paused until the third harvest, as the installation of L_0 plots lasted until early summer (Figure 1). This third harvest was used as a starting reference to check for uniform start conditions. After the third harvest, fertiliser treatments were resumed (cattle slurry or mineral N as ammonium nitrate). Therefore, two fertiliser application events and their corresponding harvests could be included in the first year's results. In Years 2 and 3, all plots except the zero fertiliser plots were fertilized once at the start of the growing season (early: start of the growing season, late: sward height of 10 cm) and, for the rest of the season, after each of the five harvests, except for the last one. This resulted in five fertiliser applications per plot in Years 2 and 3, respectively. During the entire experiment, the weather conditions were considered for the instant of time to apply slurry, avoiding application at high temperatures, wind or heavy rain. With a few exceptions, the precipitation amount between slurry application and the respective subsequent harvest was at least 32 mm (with one exception in Year 3 with only 6 mm) (Table S7).

The targeted N amount at both sites was 30 kg NH_4^+-N ha^{-1} per application. At Tänikon, the ammonium concentration of unaltered and extra diluted slurry was determined by a quick test (Quantofix N Volumeter) prior to each application, and the slurry amount was adapted accordingly. At Arenenberg, the slurry application rate was fixed at 40 m^3 ha^{-1} due to practical reasons (farm devices). Consequently, the amounts of N applied at Arenenberg varied among the different application events, depending on the N concentration of the slurry used (Table S6). At both sites, we used lateral distribution tests to ensure that the application rate did not differ among the different types of application equipment. Slurry samples were collected at each application and analysed for total nitrogen (N_{tot}), NH_4^+-N, P, K, Mg and DM contents. This allowed the calculation of a mean application rate per regrowth of 29 kg NH_4^+-N ha^{-1} at Tänikon and 34 kg NH_4^+-N ha^{-1} at Arenenberg. All slurry analyses were performed according to the reference methods of the Swiss Agricultural Research Stations (FAL et al. 1998).

Mineral N was applied on the same or the following day of the slurry applications. The same quantity of P and K was applied in mineral form to these plots as the P and K quantities received with the slurry applications by the slurry-fertilised plots.

2.4 | Determination of Dry Matter Yield and Forage N Content

Starting with the third cut in summer 2012, plots were harvested every 4–5 weeks after late slurry application with a Hege 212 plot harvester adjusted at a 6 cm cutting height. (Figure 1) Biomass yield was measured on a 1.50 m wide strip running the length at the center of each plot to avoid border effects. One plant sample per plot and harvest was oven-dried for 48 h at 65°C to calculate DM yield. Plant samples were then ground and analysed for their total N content by thermal conductometry (Dumas) with an automatic system (vario MAX CN, Elementar). N yield was calculated by multiplying the N content with the DM yield.

2.5 | Determination of Mineral Fertiliser Equivalence and Apparent N Recovery

The mineral fertiliser equivalence (MFE) for N indicates the amount of mineral N fertiliser needed to reach a yield identical to that of the slurry fertilised plots. To avoid potential effects of treatment-induced modification of legume proportions, MFE was calculated only for L_0 swards. The mineral N fertiliser–yield relationships obtained for each site and each application timing with the mineral N fertiliser series were used to determine the MFE. Here, we present the MFE based on N yield. Simple linear regressions between the amount of applied mineral N fertiliser and N yield were calculated (Figure 2). The MFE of the slurry treatments ($MFE_{(i)}$) was calculated with Equation (1) as the amount of mineral N fertiliser required for the mean N yield of the treatments ($N_{yield(i)}$) according to the site- and timing-specific regression:

$$\mathrm{MFE}_{(i)} = \left(N_{\mathrm{yield}(i)} - \alpha_{(\min)}\right) / \beta_{(\min)} \tag{1}$$

where $\alpha_{(min)}$ and $\beta_{(min)}$ are respectively the slope and the intercept of the linear regression of N yield as a function of the amount of applied mineral N fertiliser.

Apparent N recovery (N_{rec}) for L_0 swards was calculated as follows:

$$N_{\mathrm{rec}(i)} = \left(N_{\mathrm{yield}(i)} - N_{\mathrm{yield}(N0)}\right) / N_{\mathrm{fert}(i)} \tag{2}$$

where $N_{yield(i)}$ is the N yield of treatment *i*, $N_{yield(N0)}$ is the N yield in the unfertilised control treatment and $N_{fert(i)}$ the amount of NH_4^+-N applied with the slurry in treatment *i*. N_{rec} was calculated based on the average values across all harvests.

2.6 | Botanical Analysis

Botanical composition was determined annually (Figure 1) about 2 weeks prior to the third harvest by the point-intercept method (Daget and Poissonet 1971), using 50 points regularly distributed along the two diagonals of the center strip used to assess yield in each plot. For the statistical analysis, the yield proportions of the botanical groups "legumes" (*Fabaceae*) and "undesired species" were calculated. The latter consisted of those species considered as agronomically undesirable because of low feeding value, low palatability, low yield or other disadvantages for forage production (Elsäßer et al. 2018). The most important representatives of this group in our experiment were the gap-fillers *Poa trivialis* L. and *Taraxacum officinale* L. (for the complete list, see Table S2c,d).

2.7 | Determination of Forage Quality

Forage quality was analysed only at Tänikon and during Year 3 (Figure 1). Plant samples were collected at the first, second and fourth harvests from all L_+ plots except TS plots fertilised with extra diluted slurry. After wilting, samples were chopped and a subsample was used to determine the forage quality parameters before ensiling (see below). The rest was ensiled in 1.5 L laboratory silos (one silo for each plot and harvest) and opened 90 days later to analyse the parameters after the completed fermentation process (henceforth named silage).

Prior to analysis, the samples were dried at 60°C for 20 h and ground to pass a 1 mm screen. The content of neutral and acid detergent fibre was determined according to ISO 16472: 2006 (aNDFom) or ISO 13906: 2008 (aADF), respectively. Ash content was determined according to ISO 5984: 2002. Clostridial spores were analysed with the MPN method (most probable number) according to Jakob (2011). After fermentation, the concentration of butyric acid of the extracts was analysed by high-performance liquid chromatography (HPLC; Summit, Thermo Fisher Scientific, Reinach, Switzerland) equipped with a nucleogel ION 300 OA 300 × 7.8 mm column and a Shodex RI-101 refractive index detector.

2.8 | Statistical Analysis

All datasets were analysed using (generalised) linear models (LM or GLM) or (generalised) linear mixed-effect models (LMM or GLMM). For the type of model, underlying distribution type and link function, see Table S4.

Equation (3) describes the basic model structure used for the Tänikon data:

$$\begin{aligned} Y \sim\ & \text{equipment} + \text{consistency} + \text{timing} + \text{sward} + \text{equipment: consistency} \\ & + \text{equipment: timing} + \text{equipment: sward} + \text{consistency: timing} \\ & + \text{consistency: sward} + \text{timing: sward} \end{aligned} \tag{3}$$

The factor 'equipment' comprised broadcast, band-spread or trailing-shoe distribution; 'consistency' was either unaltered or extra diluted slurry; 'timing' was early or late; and 'sward' was either with or without legumes.

Equation (4) describes the basic model structure used for the Arenenberg data:

$$\begin{aligned} Y \sim\ & \text{equipment} + \text{timing} + \text{sward} + \text{equipment: timing} \\ & + \text{equipment: sward} + \text{timing: sward} \end{aligned} \tag{4}$$

Unlike the Tänikon data, a block factor was introduced as a random factor (random intercept).

For response variables 'DM yield', 'forage N content' and 'proportion of undesired species', the basic model structure was used. For response variables 'MFE', 'N_{rec}', 'legume proportion' and 'forage quality parameters' data were analysed using a reduced model structure based on either of the equations above (Table S4).

Inference on fixed main effects was determined by single-term deletion from the main effects model (each effect in turn) and subsequent likelihood ratio tests. Interactions were similarly tested but from a model that included all two-way interactions.

Given significant main effects in the model ($p < 0.05$), differences between their levels were tested using the Tukey Range Test (Tukey 1959). Given significant interaction effects, levels of one factor were tested within the levels of the other factor. All analyses were performed using the statistical software R (R Core Team 2025) and the packages glmmTMB (Brooks et al. 2017), car (Fox and Weisberg 2019), multcomp (Hothorn et al. 2008) and DHARMa (Hartig 2022).

3 | Results

3.1 | Dry Matter Yield

The treatment effects on DM yield were largely consistent across both experimental sites (Table 1 and Table S1a). However, there was a difference concerning the effect of the slurry distribution equipment. Whereas this difference was not significant at Tänikon, it was highly significant at Arenenberg ($p < 0.001$), where BS increased DM yield by 9% compared with BC. The effect of slurry consistency was significant ($p < 0.01$), with extra diluted slurry (Table S6: average reduction of DM content by 41%) resulting in a yield increase of 6%. The effect of application timing did not significantly affect the yield at either site. The effect of sward type was highly significant at both sites ($p < 0.001$), revealing a yield advantage of L_+ swards of 19% at Tänikon and 21% at Arenenberg. In our experiment, this was therefore the most striking effect on DM yield. There were no significant interaction effects in the analysis of the 3-year yield, despite significant interaction effects at Tänikon in Year 3 (Table S1a: $p < 0.05$: equipment × consistency and consistency × sward) and at Arenenberg in Year 2 (equipment × timing). However, no significant differences were revealed in the post hoc tests (pairwise comparisons).

3.2 | Forage N Content

Forage N content was not significantly affected by distribution equipment or slurry consistency (Table 1 and Table S1b). The effect of timing was significant at both sites ($p < 0.001$ at Tänikon and $p < 0.05$ at Arenenberg). Averaged over all harvests of the experiment, N content increased by late compared with early slurry application by 6% at Tänikon and 4% at Arenenberg. Sward type strongly affected N content at both sites ($p < 0.001$): The presence of legumes increased forage N content by 12% and 17% at Tänikon and Arenenberg, respectively. There were no significant interaction effects in the analysis of the three-year forage N content, but there were significant interaction effects at Tänikon in Year 3 (Table S1b: $p < 0.05$: equipment × consistency) and at Arenenberg in Year 2 (equipment × sward). As for DM yield, no significant differences could be detected in post hoc tests.

3.3 | N Utilisation Parameters

The yield response to mineral N fertiliser was +27.0 kg DM kg^{-1} N at Tänikon, and +28.7 kg DM kg^{-1} N at Arenenberg (Figure 2).

Mineral fertiliser equivalence (MFE) was not affected by the tested distribution equipment at Tänikon, whereas there was a significant effect at Arenenberg ($p < 0.05$), with an 18% higher MFE for BS compared with BC (Table 1 and Table S1c). The effect of slurry consistency (only tested at Tänikon) was significant ($p < 0.01$), and MFE was increased by 24% with extra dilution. Application timing did not significantly affect MFE at the two sites.

TABLE 1 | Yield, forage N content and N use efficiency parameters.

	Tänikon								Arenenberg							
	DM yield		N content		MFE (N)		N_{rec} (NH_4^+-N)		DM yield		N content		MFE (N)		N_{rec} (NH_4^+-N)	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Distribution equipment																
BC	20.6	0.51	2.05	0.03	18.3	1.44	0.42	0.04	23.9^{a}	0.77	2.47	0.07	22.4^{a}	1.64	0.67^{a}	0.05
BS	20.3	0.58	2.01	0.04	16.1	1.43	0.36	0.04	26.0^{b}	0.89	2.48	0.06	26.5^{b}	1.53	0.79^{b}	0.05
TS	21.3	0.47	2.06	0.03	19.9	1.14	0.46	0.03	—		—		—		—	
Slurry consistency																
Unaltered dilution	20.2^{a}	0.44	2.04	0.03	16.2^{a}	1.03	0.37^{a}	0.03	—		—		—		—	
Extra dilution	21.3^{b}	0.39	2.04	0.03	20.0^{b}	1.08	0.46^{b}	0.03	—		—		—		—	
Application timing																
Early	21.0	0.43	1.99^{a}	0.02	18.2	1.16	0.40	0.03	25.0	0.91	2.43^{a}	0.06	23.1	1.76	0.66^{a}	0.04
Late	20.5	0.42	2.10^{b}	0.03	18.1	1.13	0.42	0.03	25.0	0.88	2.53^{b}	0.06	25.8	1.70	0.80^{b}	0.05
Sward type																
L_0	19.0^{a}	0.28	1.92^{a}	0.02	—		—		22.6^{a}	0.39	2.28^{a}	0.03	—		—	
L_+	22.5^{b}	0.33	2.16^{b}	0.02	—		—		27.4^{b}	0.62	2.67^{b}	0.03	—		—	

Note: TS and slurry consistency were not tested at Arenenberg. MFE and N_{rec} were evaluated only for L_0 swards. Letters indicating significant differences are only given for factors that are significant ($p<0.05$) in the model of the statistical analysis (Table S1a–d). Shown are the means over the entire period of the experiment and averaged for each factor level (main effects). Dry matter (DM) yield ($t\,ha^{-1}$) is shown as the sum over the entire period of the experiment, N content (%), mineral fertiliser equivalence (MFE, kg N ha^{-1} $harvest^{-1}$) and apparent proportion of slurry-NH_4^+-N recovered in the harvested plant material (N_{rec}) are shown as the weighted averages per harvest. Over the entire period, no interaction between factors was significant (Table S1a–d).

Abbreviations: BC, broadcast; BS, band-spread; L_0/L_+, swards without/with legumes; SEM, standard error of the mean; TS, trailing-shoe.

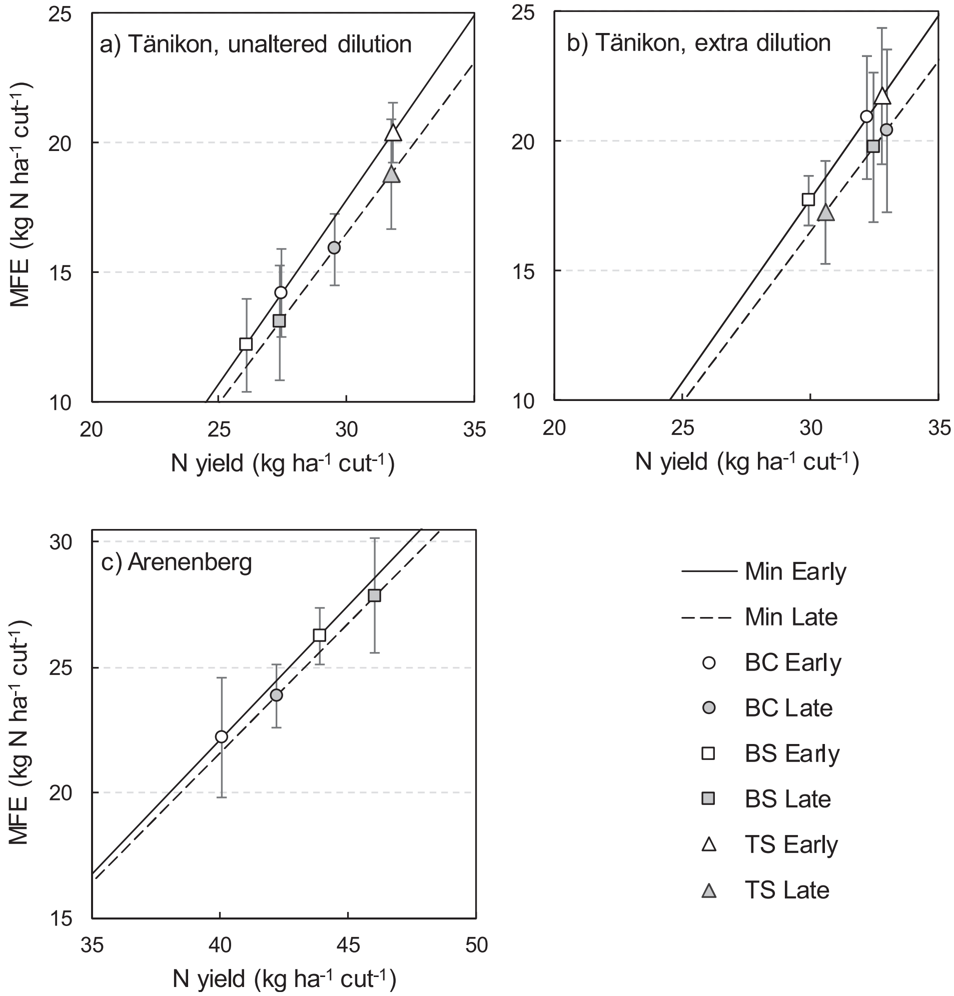

FIGURE 2 | Mineral fertiliser equivalence (MFE) for L_0 plots of the different types of equipment for (a) unaltered and (b) extra slurry dilution for Tänikon and (c) Arenenberg (only one slurry consistency). Regression lines to calculate MFE were fitted to the N yield of minerally fertilised L_0 plots (different regressions for early and late applied fertiliser: Min Early and Min Late, respectively). BC, broadcast; BS, band-spread; TS, trailing-shoe. The error bars show the standard error of the mean.

Apparent N recovery (N_{rec}) was clearly lower at Tänikon than at Arenenberg (Table 1; $p < 0.001$). The treatment effects on this parameter were similar to the effects on MFE. Distribution equipment caused no significant differences at Tänikon, whereas at Arenenberg, the effect was significant (Table S1d: $p < 0.05$). BS increased N_{rec} by 18% compared with BC at this site. A significant effect on N_{rec} was also observed for slurry consistency ($p < 0.05$), resulting in a 24% increase with extra diluted slurry compared with unaltered slurry. Application timing did not influence N_{rec} at Tänikon but had a significant effect at Arenenberg ($p < 0.05$). N_{rec} was increased by 21% when using late compared with early application.

For both MFE and N_{rec}, no significant interaction effects were revealed (Table S1c,d).

3.4 | Botanical Composition

Legume proportion in L_+ swards was not significantly affected by any experimental treatment at the two sites. However, significant effects were found for the fraction of undesired species (analysed over L_+ and L_0 swards) at both sites (Table 2 and Table S2a). At Tänikon, the main effects 'slurry consistency' ($p < 0.01$) and 'application timing' ($p < 0.05$) were significant. Slurry with unaltered dilution or an early application increased the proportion of undesired species to almost 10% compared with 6% undesired species when using extra diluted slurry or late application. A significant effect was also observed for the interaction of equipment and consistency at this site ($p < 0.05$). When slurry was BC distributed, unaltered slurry favored undesired species (not shown: 11% vs. 4%). At Arenenberg, only distribution equipment caused a significant effect ($p < 0.05$), but this finding was inconsistent (Table S2b). At this site, the proportion of undesired species was significantly higher with BS compared with BC in Year 2 but less in Year 3. In both years, undesired species increased to 30% with BS compared with 23% with BC.

3.5 | Forage Quality

At Harvest 1, the plant material was derived from a rather early stage with a low acid detergent fibre (ADF) and neutral detergent

TABLE 2 | Proportions of legumes and undesired species averaged over years 2 and 3 (%).

	Tänikon						Arenenberg					
	Legume species			Undesired species(1)			Legume species			Undesired species		
	Mean	−SEM	+SEM	Mean	−SEM	+SEM	Mean	−SEM	+SEM	Mean	−SEM	+SEM
Distribution equipment												
BC	18.8	1.7	1.9	6.7	0.9	1.1	19.7	1.7	1.8	23.2[a]	1.8	1.9
BS	16.8	1.7	1.8	7.5	1.0	1.2	20.5	1.7	1.8	29.8[b]	2.1	2.2
TS	22.1	1.9	2.0	8.9	1.1	1.2		—			—	
Slurry consistency												
Unaltered dilution	18.6	1.5	1.6	9.6[b]	0.9	1.0		—			—	
Extra dilution	19.9	1.5	1.6	6.1[a]	0.7	0.8		—			—	
Application timing												
Early	17.6	1.4	1.5	9.3[b]	0.9	1.0	20.5	1.7	1.8	24.9	1.9	2.0
Late	20.8	1.5	1.6	6.3[a]	0.8	0.9	19.6	1.7	1.8	27.9	2.1	2.1
Sward type												
L_0		—		8.4	1.0	1.1		—		28.1	2.3	2.4
L_+		—		7.3	0.9	1.0		—		25.2	1.8	1.8

Note: (1)Unaltered dilution[b], extra dilution[a] for application with BC. TS and slurry consistency were not tested at Arenenberg. Legume proportions are only relevant for L_+ swards, not for L_0 swards. Letters indicating significant differences are only given for factors (respectively factor-combinations if below the table) that are significant ($p<0.05$) in the model of the statistical analysis (Table S2a). Shown are the means of each experimental factor level (main effects). Values were derived from the models instead of measured values for the correction of initial proportions. +SEM and −SEM may differ because of the use of a logit-link function in the statistical analysis. In case of a significant interaction between factors, differences between treatments are specified in the footnote(1).
Abbreviations: BC, broadcast; BS, band-spread; L_0/L_+, swards without/with legumes; SEM, standard error of the mean; TS, trailing-shoe.

fibre (NDF) content. At Harvest 2, the plots were cut at a rather late stage and at Harvest 4, they were cut at an intermediate stage. Wilting degrees were within the range of recommendation for Harvests 1 and 2 but slightly below the range for Harvest 4 (42%, 35% and 28% DM, respectively). At all three harvests, raw ash contents were low, allowing for the production of proper forage, which correlated well with the relatively low clostridial spore occurrence in the plant material before ensiling. In the silage, butyric acid content was low at Harvest 1 but increased at Harvests 2 and 4 (Table 3).

Effects of experimental treatments on forage quality parameters revealed ambiguous results, both among the three harvests and among the tested parameters (Table 3 and Table S3).

The ADF content was significantly affected by the distribution equipment at Harvest 1 ($p<0.001$), with a 5% increase with low-emission equipment compared with BC, on average. No significant effects on ADF were observed at Harvests 2 and 4. The NDF content was not significantly affected by any treatment at any harvest.

Raw ash content was significantly affected by timing at Harvest 1 and 4 (but not Harvest 2) ($p<0.05$ and $p<0.001$ at Harvest 1 and 4, respectively). Late application caused a 5% and 6% increase compared with early application. At Harvest 1, our analysis revealed an additional timing × equipment interaction effect ($p<0.001$), with increased raw ash values for BC distributed and late application (not shown: 14% increase compared with early BC application).

Clostridial spore occurrence measured as most probable number in the plant material before ensiling (MPN g^{-1}), was significantly affected by the experimental treatments at all three harvests. At Harvest 1, MPN g^{-1} was 150% higher ($p<0.05$) with the unaltered compared with the extra diluted slurry. At Harvest 2, equipment and timing and the combination of both had significant effects on MPN g^{-1} ($p<0.05$). TS distribution caused a 115% increase compared with BS, and late application resulted in a 122% increase compared with early application. When slurry was applied early, a 319% increase was observed with TS compared with BC. When slurry was applied late, clostridial spore occurrence increased by 260% for BC compared with BS. At Harvest 4, it was affected by the distribution equipment ($p<0.05$), with a 34% increase for BS compared with BC.

The butyric acid content of the silage was only significantly affected at Harvest 1 (equipment effect $p<0.05$), inflated by a factor of three by TS compared with BC.

TABLE 3 | Acid detergent fibre (g ADF kg^{-1} DM), raw ash (g kg^{-1} DM) and clostridial spores (most probable number g^{-1}) for plant material before ensiling and butyric acid (g kg^{-1} DM) in silage.

	ADF[(1)]		Raw ash[(2)]		Clostrids[(3)]		Butyric acid	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Harvest 1								
Distribution equipment								
BC	176.3[a]	1.9	82.3	2.0	89.8	40.5	1.6[a]	0.4
BS	184.3[b]	2	85.2	1.2	59.5	14.8	2.1[ab]	0.6
TS	187.2[b]	1.1	88.7	2.2	129.7	30.6	4.8[b]	1.7
Slurry consistency								
Unaltered dilution	181.4	1.8	85.3	1.5	112.7[b]	27.3	2.7	0.8
Extra dilution	182.0	2.1	83.8	1.6	45.1[a]	15.7	2.1	0.4
Application timing								
Early	181.5	1.1	82.7[a]	1.6	75.2	24.8	2.8	0.6
Late	181.7	2.4	86.7[b]	1.3	96.1	27.7	2.1	0.7
Harvest 2								
Distribution equipment								
BC	373.2	2.5	74	1.2	162.8[ab]	63.6	24.6	1.3
BS	362.1	3.5	72.8	1.1	64.4[a]	10.7	23.2	0.9
TS	369.0	6.5	73.3	2	138.3[b]	48.8	24.2	2.6
Slurry consistency								
Unaltered dilution	368.1	3.4	73.8	1	104.2	25.5	24.1	1.1
Extra dilution	367.6	2.7	72.8	1.1	140	59.9	23.8	1.2
Application timing								
Early	369.4	3	73.4	0.8	73.5[a]	22.8	22.8	0.9
Late	366.4	3.5	73.4	1.3	163.5[b]	49.3	25	1.2
Harvest 4								
Distribution equipment								
BC	268.8	2.2	96.3	1.5	5.0[a]	0.0	26.4	1.3
BS	264.3	3.1	96.1	1.3	6.7[b]	0.7	23.6	1.4
TS	266.7	2.4	94.3	1.3	5.8[ab]	0.8	29.2	2.7
Slurry consistency								
Unaltered dilution	267.3	1.4	95.5	0.9	5.8	0.5	27.3	1.3
Extra dilution	265.5	3.5	96.3	1.6	5.8	0.6	23.7	1.3
Application timing								
Early	265.2	2.2	93.1[a]	0.7	5.7	0.5	24.4	1.3
Late	267.9	2.3	98.6[b]	1.1	6.0	0.5	27.3	1.4

Note: [(1)]Neutral detergent fibre is not shown as no significant differences among treatment means were found (Table S3). [(2)]Harvest 1: BC: early[a], late[b]; early: BC[a]—BS[ab]—TS[b]; late: BC[b]—BS[a]—TS[ab]. [(3)]Harvest 2: early: BC[a]—BS[b]—TS[b]; BC: early[a]—late[b]. Letters indicating significant differences are only given for factors (respectively factor-combinations if below the table) that are significant ($p < 0.05$) in the model of the statistical analysis (Table S3). Forage parameters were measured at Tänikon for Harvest 1, 2 and 4 in Year 3 (only L+ swards). Shown are the means of each experimental factor level (main effects). BC, broadcast; BS, band-spread; TS, trailing-shoe; SEM, standard error of the mean. In case of a significant interaction between factors, differences between treatments are specified in the footnotes (1) to (3).

4 | Discussion

4.1 | Yield and Nitrogen Utilisation: Positive Effects of Band-Spreading and Delayed Application at Arenenberg and of Slurry Dilution at Tänikon

4.1.1 | Yield Response to Mineral N Fertiliser Applications

The yield response of the L_0 swards to mineral N fertiliser (27 and 29 kg DM kg^{-1} N at Tänikon and Arenenberg, respectively) was in the upper range of the expected yield response of temperate grass swards (Whitehead 2000), showing that higher N availability clearly led to higher yields at both sites. Moreover, the standard error of the yield means was only 2%–4% across the different fertilisation treatments and the two sites. Thus, non-significant treatment effects were neither due to a lack of responsiveness of the grasslands to N availability nor to unexpectedly high variability among replicates.

4.1.2 | Distribution Equipment

The effects of distribution equipment differed between Tänikon and Arenenberg. Such inconsistent yield effects of low-emission equipment are in line with earlier studies conducted on grasslands. Some of these studies revealed significant differences between broadcast, band-spread and/or trailing-shoe equipment (Lorenz and Steffens 1997; Bittman et al. 1999; Laws et al. 2002; Carter et al. 2010; Hoekstra et al. 2010; Lalor et al. 2011), while others did not reveal any significant differences (Morken 1991; Smith et al. 2000; Chen et al. 2001; Kayser et al. 2015; Seidel et al. 2017). Negative yield effects of band-spread and trailing-shoe distribution have, to the best of our knowledge, never been reported. Among the results available in the literature, positive yield effects of low-emission equipment were generally associated with proportions of applied NH_4^+-N recovered in the harvested plant material (N_{rec}) being above about 0.5. By contrast, trials with N_{rec} below this value did not show any effect of the application equipment. Such a relationship between N_{rec} and significant equipment effects was also observed in our experiment.

Across all treatments and the entire experimental period, N_{rec} was 0.41 at Tänikon, which indicates that about 60% of the applied NH_4^+-N was not recovered in the harvested plant material. This suggests that at Tänikon, the proportion of slurry NH_4^+-N lost as ammonia into the atmosphere (about 20% in Webb et al. 2010; Häni et al. 2016; Andersson et al. 2023) was much lower than the proportion not recovered in the plants. Thus, processes other than ammonia emissions must have been highly relevant for the low recovery of slurry NH_4^+-N in Tänikon, which could have offset the expected reduction of ammonia emissions by low-emission equipment with respect to the amount of slurry N available for plant uptake. This is also supported by the fact that the apparent N recovery in the mineral fertiliser series was lower in Tänikon (73%) than in Arenenberg (95%). We hypothesise that nitrate leaching may have contributed to the low N_{rec}, as precipitation was much higher at this site than at Arenenberg (Figure S1: about 60% higher). However, the differences in N_{rec} among both sites cannot be fully explained by nitrate leaching, as N losses in grasslands through this pathway are usually small at the level of fertiliser application used in our study (Maris et al. 2021; Nyfeler et al. 2024). The much higher soil clay content (40% vs. 20% clay) at Tänikon could have also contributed to the lower N_{rec} at this site by facilitating the immobilisation of the applied NH_4^+-N (Zhang et al. 2022).

By contrast, at Arenenberg, the average N_{rec} was 0.73, which signifies that only about one quarter of the applied NH_4^+-N was not recovered in the harvested plant material. Considering an average ammonia loss of 20% of slurry NH_4^+-N with BC, as reported in the literature (Webb et al. 2010), we assume that ammonia emissions have played a predominant role in the loss of N. Thus, differences in N utilisation between BC and low-emission equipment may have been more easily detectable than at Tänikon. With BS, 79% of the applied 34 kg NH_4^+-N ha^{-1} was recovered in the harvested plant material, compared with 67% with BC. Thus, 4.1 kg N was additionally recovered per slurry application with the low-emission equipment, resulting in the observed benefits in terms of DM yield and MFE when using BS. This additional N recovered in the plants is in the range of the abatement in ammonia emissions brought about by BS compared with BC, as reported by Häni et al. (2016) for grasslands under Swiss conditions: if 20% of the applied slurry NH_4^+-N is lost as ammonia with BC (Webb et al. 2010) and the use of BS reduces these losses by half (Häni et al. 2016), the low-emission equipment would reduce ammonia losses by 3.5 kg N ha^{-1} at each application of 34 kg NH_4^+-N ha^{-1}.

In intensively managed agricultural grasslands, total N inputs by fertiliser, symbiotic fixation and atmospheric deposition can reach 350–400 kg N ha^{-1} $yr.^{-1}$ in grass-legume mixtures with legume proportions in the range of those in our experiment (Thers et al. 2022; Nyfeler et al. 2024). Moreover, mineralisation processes may further contribute 50–100 kg N ha^{-1} $yr.^{-1}$ to the amount of N available to the plant community (Sørensen and Jensen 1995; Schröder 2005; Nyfeler et al. 2011). In terms of plant available N, abatement in ammonia emissions by low-emission equipment therefore represents only a small fraction of the total (3%–4%). The significant positive effect of BS on yield observed for the grass-legume mixtures at Arenenberg is therefore remarkable.

4.1.3 | Slurry Dilution

Dilution of slurry with water results in (at least) three positive effects in terms of N availability to the plants: (i) less ammonia is lost when exposed to the atmosphere with increased dilution, (ii) slurry better infiltrates the soil, reducing exposure time and ammonia emissions, and (iii) slurry TAN can be captured more rapidly and efficiently by plant roots (Øyen et al. 1995; Rodhe 2003; Sommer et al. 2006; Mkhabela et al. 2009). Correspondingly, N utilisation and DM yield were significantly improved by slurry dilution in our experiment (Table 1: 5%, 23% and 24% for DM yield, MFE and N_{rec}, respectively). These effects of slurry dilution were not strongly influenced by the equipment used, as the three-year analysis showed the equipment × consistency interaction was only significant at $p < 0.1$ for DM yield and not significant for the other parameters (Table S1a–d). There is some reported evidence that TS and injection could be better suited for the application of viscous slurry than other equipment (Mattila et al. 2003). In our experiment, the equipment × consistency interaction was significant only in Year 3 with respect to yield and N content (Table S1a,b). Nevertheless, Figure 2 shows that MFE was clearly improved by slurry dilution when spread with BC or BS, but much less so with TS, which is in accordance with expectations. We conclude that slurry dilution is an interesting and easily applicable method for improving the MFE of slurry applications with BS.

4.1.4 | Timing

A slurry application delayed by a few days rather than promptly after harvesting, attempts to reduce ammonia losses by (i) applying the nutrients during a time of active plant growth (higher sink for N) and, in the case of low-emission equipment, (ii) placing the slurry below a canopy to protect it from wind and sun (Misselbrook et al. 2002; Thorman et al. 2008). At Arenenberg, delaying had a positive effect on N_{rec}, which was similar in strength to the effect of BS compared with BC. Nevertheless, delayed application increased forage N content but not yield, while the opposite was observed for BS vs. BC (no effect on forage N content, but increased DM yield by BS). As the equipment × timing interaction was not significant for DM yield or N content (Table S1a,b), we conclude that the best combination at Arenenberg was delayed BS application. At Tänikon, by contrast, we could not observe any advantage of delaying application as there were no significant effects on yield, MFE or N_{rec}.

Our inconsistent findings are in line with the literature: Hoekstra et al. (2010) observed beneficial effects on yield and N_{rec} by a 14-day delay compared with immediate application after the preceding cut in summer but not in spring (study with TS equipment). However, a negative effect was found for a 7- to 19-day delay in an experiment also using TS equipment on an adjacent field (Lalor et al. 2013). Negative delay effects were also reported by Wightman et al. (1997) (8-day delay vs. immediate application with BC) and Bittman et al. (1999) in spring (delays of 7–10 vs. 2–3 days with BS and TS). In the latter experiment, however, yield differences disappeared for summer and autumn applications, an effect supported by Coblentz et al. (2014) who compared 1- or 2-week delays with immediate application in summer. As discussed above, the relative importance of ammonia emissions to the total amount of slurry NH_4^+-N not recovered in the harvested biomass must have been lower in Tänikon than in Arenenberg. This might explain—at least partly—the difference in the effect of application timing between Arenenberg and Tänikon.

Delayed application may be particularly disadvantageous to plant growth when distributing viscous slurry with BC, because this may increase the risk of scorching by the slurry (Prins and Snijders 1987; Wightman et al. 1997). The relatively modest DM content (4.1%) of the unaltered slurry used at Tänikon could have contributed to the lack of interaction effects between type of equipment, consistency or timing with respect to yield, MFE and N_{rec}. Indeed, such DM content indicates that a significant amount of water was flowing into the slurry during storage on the farm where it originated (Richner et al. 2017).

4.2 | Botanical Composition: Variable Effects on Undesired Species Across Sites; No Observed Impact on Legumes

Effects of large differences in N fertiliser application on legume proportion can be clearly observed within 2 years, as exemplified by Oyharçabal et al. (2024). In our experiment, however, none of the factors affected the legume proportion of the swards. The only relatively small differences in MFE of the slurry due to distribution equipment, consistency and/or application timing (Table 1) may not have been great enough to impact legume proportion within the 2.5 years of our experiment. The literature review by Humbert et al. (2016) nevertheless shows that small differences in N inputs can add up over long periods of time to influence the botanical composition of grasslands. Long-term studies on the effects of slurry application methods on the plant communities of permanent grasslands would therefore be of great interest.

Significant smothering or scorching effects of the slurry application events on legume proportion were not observed in our experiment. As *Trifolium repens* L. was by far the dominant legume species at both sites, potential smothering or scorching (Wightman et al. 1997) could have easily been compensated by this species due to its rapid stoloniferous growth habit.

At Arenenberg, but not at Tänikon, undesired species were significantly favored by BS equipment. The dominant undesired species at Arenenberg were *Taraxacum officinale* L. and *Poa trivialis* L. (Tab S2d), which are well-known undesired gap fillers (Haggar 1971). Gaps in the sward may have been created by smothering or scorching within the slurry bands with BS application (Prins and Snijders 1987; Rodhe 2003) and subsequently invaded by undesired rather than preferred species at Arenenberg (Parish 1987; Barthram et al. 2005).

At Tänikon in contrast, preferred forage grass species that are able to spread through rhizomes (*Poa pratensis* L. and, to a certain extent, *Lolium perenne* L. (see Brock and Fletcher 1993)) were markedly more abundant, while undesired gap fillers were considerably less abundant compared with Arenenberg (Table S2c). Therefore, gaps created by low-emission equipment may have been filled up predominantly by high-value grass species (and *Trifolium repens* L.). Consequently, no significant effects on the proportion of undesired species were revealed at Tänikon.

Undesired species were significantly favored by unaltered slurry compared with slurry with extra dilution. The risk for smothering and scorching, and thus the risk for gaps, may be reduced with a higher dilution (Prins and Snijders 1987). The equipment × consistency interaction was significant, and the positive effect (i.e., less undesired species) of extra dilution was significant for BC, which would indicate a reduction of scorching rather than smothering. Nevertheless, the differences in the proportion of undesired species were only a few percentage points; thus, these results do not allow drawing firm conclusions.

Undesired species were also significantly favoured by early compared with late application at Tänikon, while this relationship was not observed at Arenenberg. This result from Tänikon is not consistent with the potentially increased smothering and wheel damage with delayed application into regrown swards reported in earlier studies (Wightman et al. 1997; Lalor et al. 2013). Given that the difference in the proportion of undesired species between early and late application (i) was not great at Tänikon (9% vs. 6%), (ii) was not significant at Arenenberg and (iii) is not supported by relationships reported elsewhere, we consider that no conclusion can be drawn from these results about the effects of early vs. late application on undesired species. Changes regarding botanical composition in grassland are complex due to numerous interactions between species, environment and management practices (Peter et al. 2008). Experiments including more sites and longer durations are therefore needed to draw meaningful conclusions about the effects of relatively small treatment differences, such as those assessed in this study, on grassland botanical composition.

4.3 | Forage Quality: No Relevant Detrimental Effects of Low-Emission Equipment but Indication of Impaired Forage Quality With Delayed Application

The effects of distribution equipment on forage quality were not consistent across the three harvests examined. Although the ADF content—as an indicator for straw residues from slurry in the forage—was increased for low-emission equipment at Harvest 1, no differences were found at Harvests 2 and 4. For BS equipment, this may be explained by slurry bands raising with the growing vegetation due to rather viscous slurry (Table S6: DM content of 5.7%, 4.7% and 2.1% at Harvest 1, 2 and 4, respectively) and the long time span between slurry application and rainfall (Table S7: 10 days without rain after early application in spring). At the same time, harvested biomass of low-emission equipment (BS and TS) at Harvest 1 was almost 25% higher compared with BC. As ADF content strongly increases with a more mature plant stage, particularly in spring (coinciding with increased biomass production), we cannot disentangle the potential effect of straw residues from the effect of larger biomass on the difference in ADF content among distribution equipment at Harvest 1. Other studies on the effects of slurry application on the quality of mown forage did neither report straw residues from slurry (Min et al. 2002) nor differences among different types of distribution equipment (Laws et al. 2002).

The Effects of distribution equipment on clostridial bacteria occurrence and butyric acid in the silage were not consistent across the three harvests. Clostridial bacteria occurrence was never beyond agronomically relevant thresholds (Borreani and Tabacco 2008) with any treatment. This could partly explain why clostridial bacteria and butyric acid did not correlate in our experiment, although these two parameters should be causally linked (Li et al. 2020). We conclude that low-emission equipment is not detrimental to forage quality.

The observed significant increase in clostridial bacteria occurrence at Harvest 1 for unaltered slurry compared with slurry with extra dilution was a factor of 2.5 (but still below the threshold for high-quality silage). This finding is in line with those of Rodhe (2003), who reported a significant relationship between the DM content of slurry and the adhesion of slurry particles to the plants. In our experiment, however, this increase did not adversely affect butyric acid content at Harvest 1, and no effects of slurry consistency were revealed at Harvests 2 and 4. From the data of our study, there is no compelling evidence that sticky slurry is associated with an increased occurrence of clostridial bacteria, and particularly, butyric acid content in the silage.

The effect of delayed slurry application was the most consistent among the tested treatments in terms of forage quality. Raw ash content (Harvests 1 and 4) and clostridial bacteria (Harvest 2) as indicators for soiling and slurry residues were significantly increased by late application compared with early application. Furthermore, these parameters might be particularly increased with TS at early application and BC at late application (significant interaction at Harvests 1 and 2). Detrimental effects of a delayed slurry application have also been demonstrated by Davies et al. (1996) (34 days before harvest), Laws et al. (2002) (14 days before harvest) and Coblentz et al. (2014) (15–29 days before harvest). From the significant interaction in our experiment, we hypothesise that soil disturbance by TS when applied to freshly cut swards could increase the risk of soiling the forage. For delayed application, however, slurry residues are more problematic when using BC. We conclude that the risk of soiling forage with slurry residues is increased for delayed slurry application but that this increase in risk is lower with low-emission equipment, especially with TS (Lalor and Schulte 2008).

5 | Conclusion

We conclude from our experiment that the use of low-emission equipment can be recommended for slurry applications on grasslands from a forage production and N utilisation point of view. This is also the case for slurry dilution, particularly when broadcast or band-spread equipment is used. Indeed, these two practical levers of action and their combination are slightly beneficial for grass yield and N utilisation without negative effects on forage cleanliness or agronomically relevant negative effects on grassland botanical composition for a 3-year term. This study also highlights the dominant influence of site conditions on the effects of slurry application methods on the utilisation by grassland of applied slurry N. This led to site-dependent responses to the application methods, although conditions for sward response to contrasted N fertiliser application were met at both experimental sites. With respect to the timing of slurry application following a harvest (immediately vs. delayed), we conclude that further studies are necessary to confirm or refute the potential trade-off between its effects on N utilisation and forage cleanliness.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Mean temperature and cumulated precipitation per month over the 3 years of the experiment and both sites. The dashed lines show the mean values for the period 2011–2021. **Data S1.** Supporting Information. **Table S1a.** Significance levels of tested factors in models to analyse dry matter yield. Models were fitted for each year and over the entire experiment, and separately for each site. $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), $p < 0.1$ (.), ns = not significant. **Table S1b.** Significance levels of tested factors in models to analyse forage N content (average over harvests). Models were fitted for each year and over the entire experiment, and separately for each site. $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), $p < 0.1$ (.), ns = not significant. **Table S1c.** Significance levels of tested factors in models to analyse mineral fertiliser equivalence (MFE) of slurry treatments in terms of harvested N in L0 plots. Models were fitted over the entire period of the experiment (average per harvest), and separately for each site. $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), $p < 0.1$ (.), ns = not significant. **Table S1d.** Significance levels of tested factors in models to analyse proportion of N in the harvested plant material recovered from slurry NH4+-N (Nrec) in L0 plots. Models were fitted over the entire period of the experiment (average per harvest), and separately for each site. $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), $p < 0.1$ (.), ns = not significant. **Table S2a.** Significance levels of tested factors in models to analyse yield proportions of legumes and undesired species at each site. Models were fitted over the Years 2 and 3, and separately for Year 2 and 3. $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), $p < 0.1$ (.), ns = not significant. **Table S2c.** Yield proportion (%) of grass (G), legume (L) and forb species (F) in L+ stands and L0 stands at Tänikon averaged for each experimental factor level. Means are shown for main species for each year (Y1-3). Species with a yield proportion < 1% were combined (see footnotes (1) and (2)). Lolium perenne (LOPE), Lolium multiflorum (LOMU), Poa pratensis (POPR), Phleum pratense (PHPR), Poa trivialis (POTR), Poa annua (POAN), Trifolium repens (TRRE), Trifolium pratense (TRPR), Taraxacum officinale (TAOF), BC = broadcast, BS = band-spread, TS = trailing shoe, L0/L+ = swards without/with legumes. Undesired species are marked in red. **Table S2d.** Yield proportion (%) of grass (G), legume (L) and forb species (F) in L+ stands and L0 stands at Arenenberg averaged for each experimental factor level. Means are shown for main species of Blocks I + II (grass-clover mixture with Poa pratensis and Festuca rubra) and Block III (with Festuca pratensis) for each year (Y1-3). Species with a yield proportion < 1% were combined (see footnotes (1) and (2)). Lolium perenne (LOPE), Lolium multiflorum (LOMU), Dactylis glomerata (DAGL), Poa pratensis (POPR), Phleum pratense (PHPR), Poa trivialis (POTR), Poa annua (POAN), Trifolium repens (TRRE), Trifolium pratense (TRPR), Medicago sativa (MESA), Taraxacum officinale (TAOF), BC = broadcast, BS = band-spread, TS = trailing shoe, L0/L+ = swards without/with legumes. Undesired species are marked in red. **Table S3.** Significance levels of tested factors in models to analyse acid detergent fibre (ADF), neutral detergent fibre (ND), raw ash and clostridial spores in plant material before ensiling, and butyric acid (BA) in the silage (only L+ swards at Tänikon in Year 3, Harvest 1, 2 and 4). Models were fitted separately for each harvest. $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), $p < 0.1$ (.), ns = not significant. **Table S4.** Type, distribution and link function of models to analyse data at Tänikon and Arenenberg. Model types were LM, linear model; LMM, linear mixed model; GLM, generalised linear model; GLMM, generalised linear mixed model. At Arenenberg, N content was the only forage content parameter to be analysed (–). **Table S5.** Soil characteristics of the study sites (soil horizon 0–20 cm). **Table S6.** Dry matter content (%) and nutrient concentrations (kg m−3) of applied slurry. Shown are the means over early and late application per harvest (H1-5). For Tänikon, the ratio of DM content of unaltered versus extra diluted slurry is given to calculate the content of nutrients in extra diluted slurry. For Arenenberg, no ratio is given as slurry was not altered. **Table S7.** Precipitation amounts (mm) between the slurry application and the corresponding harvest (H1-5) over the 3 years of the experiment and both locations. Days until the onset of precipitation in brackets.