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Carbon, nitrogen, phosphorus and potassium flows and losses from solid and semi-solid manures produced by beef cattle in deep litter barns and tied stalls

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ABSTRACT

Nutrient losses have to be avoided in agricultural systems for agronomic and environmental reasons. However, they are known to be potentially large and variable. Results from twenty nine trials aiming at quantifying nitrogen (N), phosphorus (P), potassium (K) and carbon (C) flows and losses from barn and manure storage for beef cattle (Belgian Blue double-muscled breed) were synthesized. They included variation in barn type (tied stall and deep litter), leading to contrasted manure types (respectively semi-solid manure and deep litter manure) of small groups ($n = 4$) of heifers or bulls.

Despite uncertainties pointed out by non-zero P or K balances, we established for manure storage, a relation between K losses by flowing out as liquid and rainfalls: K lost (%K stored) = $100*(1–0.99*e^{(-0.00078*\text{rainfalls (mm)})}$; $n = 28$). We also emphasized, within the particular set of data treated, the effects of barn type (approached by STRAWr; kg straw kg^{-1} DM in feed), manure storage duration (d), nitrogen in feed concentration (NFEED; g N kg^{-1} DM) and storage temperature (°C) on N losses from the whole system (N lost (% N input) $= -33.33 + 0.0869$*storage duration + 1.11*storage temperature + 27.9*STRAWr + 1.278*NFEED; $r^2 = 0.700$; $n = 29$) such as the strong relation between C and N losses during manure store per day of storage (N lost (% N stored d^{-1}) = 0.038 + 0.617*C lost (% C stored d^{-1})). We also observed that, even if N and C inputs in the system were higher in deep litter systems due to straw supply, the amounts of N and C remaining in the manure after being stored were very similar, indicating higher losses of these nutrients from deep litter systems compared to tied stalls. These findings will further help in modeling cattle housing systems for nutrient cycling optimization. However, the relations established have to be validated for other tied stall and deep litter systems regarding the diversity in manure management for each barn type. Furthermore, when comparing manure provided under different housing systems, other agronomical (e.g. their sanitization due to heat increase when stored, ease of application to soil after storage) or environmental (e.g. greenhouse gas emissions) aspects have to be considered.

1. Introduction

Optimized circular management of nutrients is essential for farming systems sustainability. From the environmental point of view (e.g. Smith et al., 2014), reducing the use of limited natural resources and avoiding emissions of harmful molecules like nitrate and phosphate to water or methane to the air is required. The contribution of cattle production systems to these emissions have been recognized globally (Steinfeld et al., 2006) and regionally (KEIW, 2013). Therefore, agreements targeting the quantification and reduction of these emissions have been signed at the global and/or European scale (e.g.: UNFCCC, 2015; Nitrate directive: EEC, 1991). In cattle production systems, for legislation (AGW, 2014), quantification of environmental impact (e.g.: IPCC, 2006; EMEP, 2013) or decision making tools development like LCA (ISO, 2006; Cederberg et al., 2013), it is advisable to develop a referential based on nutrient flows adapted to local specificities (Van Stappen et al., 2018). However, these flows are characterized by large variabilities related, among others, to manure composition, itself dependent on manure management systems (Webb et al., 2012) driven, for example, by diverse barn systems like those occurring

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in Wallonia (AGW, 2014) and by animal feeding strategies (e.g.: for protein content in cattle diet: Dijkstra et al., 2013). Nutrient flows and their losses from agricultural system can be calculated using mass balance (Öborn et al., 2003). This method may require the estimation of nutrient amount in the different compartments of the system, like in cattle body live weigh (lw). However, diverse values can be found in the literature (e.g.: 2 (Haas et al., 2002) and 2.5 (Meschy and Guéguen, 1995) g kg^{-1} lw for K, or 6 (Haas et al., 2002), 7 (Corpen, 2001), 6.5 to 7.3 (Koelsch and Lesoing, 1999), 9 (Meschy and Guéguen, 1995) and 12 (Clark et al., 2007) g kg^{-1} lw for P) leading to potential bias in these balances when using not adapted reference values. The variability in nutrient flow and its reliability have to be explored to find optimized strategies for efficient nutrient conversion to agricultural products while limiting their losses as molecules damaging to the environment.

Therefore, we explore data from several trials to quantify nitrogen (N), phosphorus (P), potassium (K) and carbon (C) flows and losses in the barn and during manure storage for two manure types - semi-solid or deep litter manures (Pain and Menzi, 2003) - as those produced mainly in beef barn systems used in Belgium (AGW, 2014; INS, 1996). Effects of management strategies such as straw supply rate, manure removal frequency, manure storage period and cattle diet are also addressed to develop reference values under contrasting situations.

2. Material and methods

2.1. Experimental facilities and factors tested

Nutrients flows were quantified in barns (Table 1) located at Libramont (49°55′43″N; 5°21′37″E, alt: 487 m a.s.l.) with 4 animals, under twenty nine manure management schemes (management x barn x cattle type, Table 1). Cattle were raised during winter periods in experimental tied stall (TS) and deep litter (DL) barns to produce semi-solid (SSM) and deep litter (DLM) manure respectively. Repetitions in time (Rep characteristic in Table 1) of experience with the same treatment were considered as different trials notably due to differences in manure storage meteorological conditions.

The animals used were heifers (H) in tied stalls (TS_H: eleven trials) and heifers in deep litter barns (DL_H: eight trials) or young bulls (B) in deep litter barns (DL_B: ten trials). The eleven trials in tied stall barns were carried out as described in Mathot et al. (2012) with production of semi-solid manure coupled to a liquid fraction (LF). The remaining eighteen trials were carried out in deep litter barns, such as described by Mathot et al. (2016), with production of deep litter manure. Basically, we tested the impacts linked to (1) the variation in the amount of straw supplied as litter and (2) manure management including storage removal frequency, storage duration and meteorological conditions that are dependent on the barn type (TS *vs* DL). In terms of manure management, in tied stalls, the semi-solid manure was removed daily from the barn to be stacked uncovered on manure storage facilities while the liquid fraction produced was collected in a tank located outside the barn. In the deep litter barns, the solid manure was accumulated for a longer duration (at least 18 days in trials 28 and 29; Mathot et al., 2016 and Table 1) under the animals before being removed to be stored. For this type of barn there was no liquid fraction produced at barn. Within a barn type the amount of straw supplied as litter (trials 2 to 7, Table 1), the cattle feed composition (trials 8 to 13 and 18 to 21 in deep litter barns with bulls and in trials 14 to 17 and 22 to 25 in tied stalls with heifers, Table 1) or the manure removal frequency (trials 26 to 29,

Table 1
Trials Barn type (TS = tied stall, DL = deep litter), Cattle type (H = heifers and B = bulls; n = 4), cattle feed (see Table 2), Manure treatment, Cattle group (1–21), Rep. = repetition in time number, start date and duration of housing and manure storage period.

Trial	Barn	Cattle Type	Feed	Manure	Cattle group	Rep.	Barn Start (date)	Barn Duration (d)	Store Start (date)	Store Duration (d)
1	TS	H	1	/[a]	1-2-3[d]	1	24/01/2006	93	25/01/2006	247
2	DL	H		Straw -[b]	1-2-3	1	24/01/2006	93	22/05/2006	130
3				Straw +	1-2-3	1	24/01/2006	93	22/05/2006	130
4	TS	H	2	Straw -	4-5-6[d]	1	6/12/2006	66	7/12/2006	278
5				Straw +	4-5-6	1	24/12/2006	59	25/12/2006	260
6	DL	H		Straw -	4-5-6	1	6/12/2006	125	4/05/2007	130
7				Straw +	4-5-6	1	6/12/2006	125	24/05/2007	130
8	DL	B	3	/	7	1	10/12/2007	42	22/01/2008	160
9				/	8	2	28/01/2007	42	11/03/2008	111
10				/	9	3	17/03/2008	42	8/05/2008	53
11			4	/	10	1	10/12/2007	42	22/01/2008	160
12				/	11	2	28/01/2007	42	11/03/2008	111
13				/	12	3	17/03/2008	42	8/05/2008	53
14	TS	H	5	/	13	1	25/11/2008	64	26/11/2008	208
15				/	14	2	16/02/2009	70	17/02/2009	125
16			6	/	14	1	25/11/2008	69	26/11/2008	208
17				/	13	2	16/02/2009	70	17/02/2009	125
18	DL	B	7	/	15	1	25/11/2008	69	4/02/2009	138
19				/	16	2	16/02/2009	70	4/05/2009	49
20			8	/	17	1	25/11/2008	69	4/02/2009	138
21				/	18	2	16/02/2009	70	4/05/2009	49
22	TS	H	9	/	19	1	16/11/2009	68	17/11/2009	136
23				/	20	2	9/03/2009	73	9/02/2010	146
24			10	/	20	1	16/11/2009	68	17/11/2009	136
25				/	19	2	9/03/2009	73	9/02/2010	146
26	DL	H	9	1x/rep	21	1	16/11/2009	66	28/01/2010	64
27				1x/rep	22	2	8/02/2010	73	4/05/2010	62
28				3x/rep[c]	22	1	16/11/2009	66	10/12/2009	113
29				3x/p	21	2	8/02/2010	73	11/03/2010	116

[a] No particular treatment. Manure from deep litter is removed at the end of the trial in the barn.
[b] For Straw - only 50% of the straw was supplied compared to Straw + (0.17 and 1.2 kg straw 100 kg^{-1} cattle live weight for TS and DL respectively).
[c] 3x means that manure from the deep litter barn was removed three times during the trial in the barn while only 1x at the end for the other trials in DL. For trial 28 the manure was accumulated under the animals for 22, 26 and 18 days. For trial 29 the manure was accumulated for 29, 26 and 18 days.
[d] Cattle group 1 to 3and 4 to were shift between treatments but without removing manure from deep litter barns at shifting time.

Table 1) and the manure storage climatic conditions (embedded in repetitions of the other trials) were also investigated.

In tied stalls, animals stayed on rubber mat. Typically 0.1 kg fresh straw 100 kg^{-1} live weight was supplied as litter behind them. In deep litter barns, the target was to supply straw under the animals with a typical rate of about 1 kg fresh straw 100 kg^{-1} lw. For both barn types a variation in litter supply was tested (trials 2 to 7; Table 1). All the semi-solid and deep litter manures produced were stored for a duration varying from 49 to 278 days on a concrete storage facility in individual compartments. Each compartment (11.2 m^2) had a separate liquid fraction collecting system leading to a 1m^3 tank.

2.2. Cattle and diet

The animals weighed on average 443 ± 26 kg and were 20 ± 1 months old in TS_H; 375 ± 25 kg and 16 ± 1 month old in DL_H and 305 ± 9 kg and 9 ± 1 month old in DL_B. Diets offered to the cattle were defined to cover their energy and protein requirements (Ministry of Agriculture, Information Service, 1990; Tamminga et al., 1994; Van Vliet, 1997) according to the Dutch cattle feeding system.

The level of protein supplied to the cattle was quantified as the ratio (DVEr) of protein available in the small intestine (DVE) supplied to the protein available in the small intestine requirement calculated from the model currently applied in Belgium, (Ministry of Agriculture, Information Service, 1992; Tamminga et al., 1994). All cattle had the opportunity to adapt themselves to their diet for at least 14 days before the beginning of the trials. Diets varied with the trials but were, on average, similar for heifers grown in DL_H and TS_H (Table 2).

2.3. Data collection and analysis

We calculated nutrient balances (Öborn et al., 2003) to study N, P, K, C and ash distributions between components of the system (animal, manure, feed, …) and losses during manure production at barn and storage phases. The system inputs were feed (refusal excluded and water included) and straw entering the barns for litter. The system outputs were cattle live weight gains (lwg) leaving the barn, manures after storage and liquid fractions (Fig. 1). The system was furthermore divided in two phases, barn and storage, to calculate intermediate balance (Out1 and Out2) and losses with equations as described at Fig. 1. Direct measurements and analysis were performed according to Mathot et al. (2012), (2016) for all the stages except for cattle lwg composition that were estimated through data from literature.

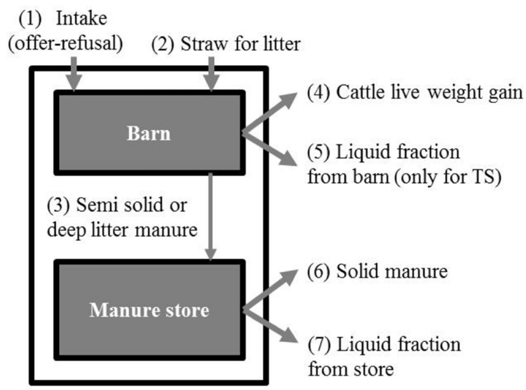
Nitrogen, ash, and C concentrations in cattle lwg were derived from De Campeneere et al. (2001) because they were recorded on cattle of the same breed and in similar feeding trials. They changed with live weight: N (g kg^{-1} lwg) = 0.0064*lw(kg) + 29.3; ash (g kg^{-1} lwg) = 0.0238*lw(kg) + 29.5; OM (g kg^{-1} lwg) = 0.158*lw(kg) + 253). The C concentration was estimated considering a C:OM ratio of 0.5 (Haas et al., 2002). Potassium and P concentration in lwg were assumed to be 2.5 g K kg^{-1} lwg (Meschy and Guéguen, 1995) and 12 g P kg^{-1} lwg (Clark et al., 2007).

Excretion by cattle can be quantified with equations 4 and 6 (Fig. 1). Equation 4 is only valid for components that are not lost as gases directly from the animal (C, as CO_2 or CH_4, e.g. Mathot et al., 2012). It relies on an estimation of cattle live weight gain composition based on literature data. Calculation of animal excretion based on the difference between manure produced and straw supply (equation 6) cannot be used for components that can be lost as gases from manures after their production by cattle (*i.e.,* C and N). Considering this, ash, P and K excretion can be quantified with both equations while N only with equation 4. Relying on the hypothesis of marginal direct N gaseous emissions from the cattle, for N, the difference between results from equations 6 and 4 is an indicator of N losses from manure in the barn. As C is lost in significant amount by the cattle itself and its manure (Mathot et al., 2012 and 2016), cattle C and DM excretions cannot be

Table 2
Diet composition, cattle size and performances (mean ± sem of the trials; TS_H: n = 11, DL_H: n = 8 and DL_B: n = 10).

Feed	Grass silage (% DM)	Maize silage	Lucerne	Straw	Spelt	Rape	Concentrate	DM g kg^{-1} FM	DVE g kg^{-1} DM	VEVI/VEM	OEB	Ash	CP	K	P	Lw kg $head^{-1}$	Dlwg g $head^{-1}$ d^{-1}	FCI kg DM kg^{-1} lwg
1	67		7		26			710	46	787	−7.8	66	97	18.6	2.7			
2	70				30			667	65	886	−6.1	74	115	22.7	3.3			
3				8			92	909	88	969	21.5	87	174	14.1	4.2			
4	35	27			13	24		591	76	892	24.5	86	164	18.7	4.7			
5				18			82	912	84	972	24.9	103	160	13.0	3.3			
6	62		6		32			521	74	907	36.5	73	168	18.0	5.3			
7				8			92	912	80	956	14.5	75	151	9.8	4.8			
8	34	25			21	20		589	63	849	−0.1	73	117	20.7	3.4			
9	45	55						703	78	910	18.1	95	147	21.4	4.8			
10	64		6		30			639	68	810	2.1	92	125	26.9	3.9			
TS_H								703 ± 34[a]	69 ± 3[a]	874 ± 17[a]	4.4 ± 3[a]	80 ± 3[a]	128 ± 6[a]	20.2 ± 1.7[a]	3.9 ± 0.2[a]	443 ± 26[a]	635 ± 58[a]	12.5 ± 0.7[a]
DL_H								696 ± 7[a]	67 ± 5[a]	873 ± 19[a]	5.6 ± 4.7[a]	83 ± 5[a]	127 ± 8[a]	21.0 ± 0.6[a]	3.9 ± 0.4[a]	375 ± 25[ab]	813 ± 82[a]	9.5 ± 0.5[ab]
DL_B								737 ± 62[a]	81 ± 2[b]	934 ± 13[b]	26.1 ± 2.1[b]	87 ± 3[a]	167 ± 2[b]	16.0 ± 0.9[b]	4.4 ± 0.2[a]	305 ± 9[b]	1258 ± 79[b]	5.9 ± 0.5[b]

TS_H, heifers in tied stalls; DL_H, heifers in deep litter barns; DL_B, bulls in deep litter barns; DM, dry matter; FM, fresh matter; DVE, digestible feed and microbial true protein in the small intestine; VEVI/VEM, energy; OEB, degraded protein balance (nutritive value of forage following the Dutch system; Van Vliet, 1997 and Tamminga et al., 1994) determined using NIRS predictions as proposed by De Boever et al. (1996); CP, crude protein (Kjeldahl Nx6.25); Lw, cattle live weight; Dlwg, cattle daily live weight gain; FCI, feed conversion ratio.



Eq 1: Losses at barn=1+2-(3+4+5)
Eq 2: Losses at store=3-(6+7)
Eq 3: Total losses=1+2-(4+5+6+7)
Eq 4: Cattle excretion estimated=1-4
Eq 5: Manure production at barn=3+5
Eq 6: Cattle excretion calculated=3+5-2
Eq 7: Manure before field application=5+6+7
Eq 8: Cattle live weight gain calculated=1-(3+5-2)
Eq 9: In=1+2
Eq 10: Out1=3+4+5
Eq 11: Out2=4+5+6+7

Fig. 1. System description and equations used for flows and losses calculation.

calculated.

2.4. Validation indicators, units and statistics

Reliability of the balances calculated was estimated considering the hypothesis that ash, P and K are not lost from the system when collecting liquid fractions (Larney et al., 2006; Oenema et al., 2007). Differences of P and K losses (equations 1 to 3; Fig. 1) from zero were thus tested for global balance reliability evaluation at barn (Out1) and system gate (Out2) but also, with equation 8 (Fig. 1), to test the literature values used for P and K exportation through cattle lwg. Potassium and P balances were considered to discuss N and C losses and the pertinence of adjusting these losses as a function of the magnitude of difference to a no P and K loss hypothesis. Nutrient excretions by cattle were calculated for comparison with reference values (AGW, 2014). Cattle performances were compared according to daily live weight gain (Dlwg) and feed conversion index (FCI) calculated as kg dry matter (DM) consumed per kg of lwg.

To avoid size effects related to cattle or trials duration, the flows and losses are mainly presented per kg of animal metabolic weight ($mw = lw^{0.75}$) per day, per total input and per animal intake (nutrient or dry matter). Other ratios are used for more specific explanations (e.g.: amount of N lost as a proportion of the N stored during manure storage).

Data were firstly analyzed on the basis of a group of treatments defined on the barn types x cattle types (i.e.: TS_H, DL_H and DL_B). Thereafter, when cattle type, in DL systems, had no influence, barn type effect was tested alone. Preliminary tests for homoscedasticity and normality were performed with Fligner-Killeen and Shapiro tests respectively (Crawley, 2011). When the hypothesis of normality and variance equality were not respected, Kruskal and Wallis and Nemenyi-tests were performed, otherwise Anova 1 and Tukey tests for multiple mean comparisons with an unbalanced model (R Core Team, 2017), with barn types x cattle types (treatment groups) as factor, were performed. Observed values were also tested against reference values (AGW, 2014), such as nitrogen excretion by cattle, using Student *t*-test or linear regressions.

Finally, trends across all the dataset were tested to identify the main parameters, such as cattle diet and meteorological conditions, influencing nutrient losses at the different stages. For N losses, linear regressions with the use of stepwise model selection by AIC were performed with the step function (Venables and Ripley, 2002) in R software. In this case, trial parameters (Table 1) were used to explain part of the variability observed. Storage duration (d) and climatic conditions, through the mean temperature over the storage period (°C), were used to include cumulative effects and climatic conditions potentially influencing organic matter degradation. The level of protein nutrition level supply to cattle was integrated as DVEr or nitrogen concentration of the feed (NFEED in g kg^{-1} dry matter). The barn type effect was approached using the straw dry matter supply for bedding to dry matter ingested by cattle ratio (STRAWr). The means are presented with their standard error (sem).

3. Results

3.1. Feed, cattle performances and reference values

Diets were, on average, very similar for heifers raised in TS and DL ($p > 0.05$), while they had a higher feeding value ($p < 0.05$) for bulls except for ash and P ($p > 0.05$) concentrations (Table 2). Cattle lw, Dlwg and FCI, significantly differed ($p < 0.05$) between heifers in TS and bulls in DL but not ($p > 0.05$) between heifer raised in TS compared to those raised on DL (Table 2). Even if characterized by intermediate values, DL_H differed significantly ($p < 0.05$) from DL_B only for daily live weight gains (813 ± 82 and 1258 ± 79 g $^{-1}$ head^{-1} d^{-1}).

Phosphorus retained by the cattle, as calculated with equation 8 (Fig. 2), was of 13.0 ± 0.9 g kg^{-1} lwg, without variation with treatment groups ($p < 0.05$) and without significant difference ($p > 0.05$) to the reference value of 12 g P kg^{-1} lwg. This parameter was marginally correlated ($p = 0.08$, $r^2 = 0.110$) to the concentration of P in the feed (min = 2.7 g kg^{-1} DM, max = 5.4 g kg^{-1} DM, mean = 4.1 ± 0.2 g kg^{-1} DM). Potassium concentrations in cattle live weight were 0.3 ± 9.2 g kg^{-1} lwg for TS_H, 21.9 ± 4.4 g kg^{-1} lwg for DL_H and 17.6 ± 3.3 g kg^{-1} lwg for DL_B. For these two last treatments, the concentrations were significantly different ($p < 0.05$) from the range of 2–2.5 g kg^{-1} lwg found in the literature. No relation ($p > 0.05$) was observed between K concentration in the feed (min = 9.9 g kg^{-1} DM, max = 27.7 g kg^{-1} DM, mean = 18.9 ± 0.8 g kg^{-1} DM) and K concentration in animal gains. For ash, concentration in animal gains were very variable (38.2 ± 16.7 g kg^{-1} lwg) but, on average, similar to reference values (38.5 ± 0.4 g kg^{-1} lwg) without any treatment effect or relation with ash concentration in feed (min = 66.4 g kg^{-1} DM, max = 103.4 g kg^{-1} DM, mean = 83.8 ± 2.2 g kg^{-1} DM).

3.2. System

3.2.1. System input

3.2.1.1. Distribution. In TS most of the inputs, ranging between 94.4 ± 0.1 % for C and 98.7 ± 0.1 % for P, came from cattle feed. In DL systems, with heifers or bulls, these proportions were lower due to higher straw inputs as litter. They ranged between 65.4 ± 1 % for C and 91.7 ± 1 % for P (Fig. 2).

3.2.1.2. Amount. Per kg of metabolic weight, cattle intakes of the three treatment groups (TS_H, DL_H and DL_B) differ for most of the parameters, but P. Intakes were significantly lower for DM and C in

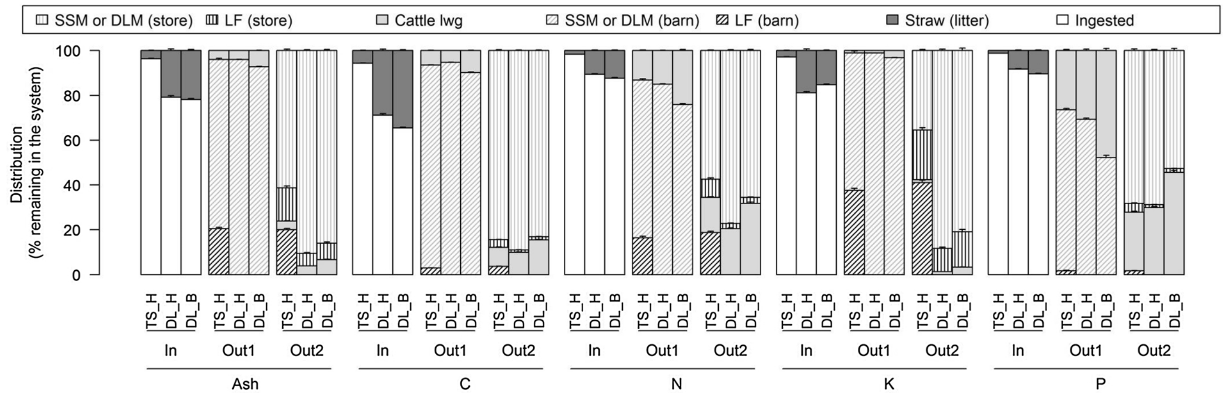


Fig. 2. Distribution (%) of the nutrients and ash remaining (not lost) in the system at the different stages of the trials (error bars are the standard error of the mean of the contribution of the particular stage/component). SSM and DLM are semi-solid manure and deep litter manure. LF is the liquid fraction collected; lwg is the exportation through cattle gains. In is input at the barns; Out1 is the output of the barn and Out2 is the output of the whole systems, *i.e.,* after manure storage.

Table 3
Mean (± sem) of the nutrients amount, at the different stages of the balance, in g kg^{-1} of mw d^{-1} at barn. n.r, not relevant (see Material and methods section).

	Ingested	Litter	Retained	Retained (Eq. 8)	Excreted (Eq 4)	Excreted (Eq 6)	Manure (Out1)	Manure (Out2)
	DM							
TS_H	79 ± 1^{a}	5 ± 0^{a}	2.4 ± 0.2^{a}	n.r.	n.r.	n.r.	36 ± 1^{a}	29 ± 2^{a}
DL_H	88 ± 2^{b}	35 ± 3^{b}	3.3 ± 0.2^{a}	n.r.	n.r.	n.r.	61 ± 3^{b}	36 ± 4^{ab}
DL_B	88 ± 3^{b}	44 ± 2^{b}	5.9 ± 0.4^{b}	n.r.	n.r.	n.r.	56 ± 1^{b}	37 ± 1^{b}
	Ash							
TS_H	6.3 ± 0.3^{a}	0.2 ± 0^{a}	0.26 ± 0.02^{a}	0.04 ± 0.21^{a}	6.02 ± 0.28^{a}	6.2 ± 0.^{4a}	6.5 ± 0.4^{a}	6.7 ± 0.3^{a}
DL_H	7.3 ± 0.5^{ab}	1.9 ± 0.2^{b}	0.36 ± 0.03^{a}	0.36 ± 0.18^{a}	6.91 ± 0.52^{a}	6.9 ± 0.6^{a}	8.8 ± 0.6^{b}	9 ± 0.6^{b}
DL_B	7.7 ± 0.5^{b}	2.1 ± 0.1^{b}	0.64 ± 0.04^{b}	1.53 ± 0.42^{b}	7.06 ± 0.47^{a}	6.2 ± 0.3^{a}	8.3 ± 0.4^{b}	9.1 ± 0.5^{b}
	C							
TS_H	35 ± 1^{a}	2 ± 0^{a}	1.1 ± 0.1^{a}	n.r.	n.r.	n.r.	15 ± 1^{a}	11.9 ± 0.8^{a}
DL_H	39 ± 1^{b}	16 ± 2^{b}	1.5 ± 0.1^{a}	n.r.	n.r.	n.r.	26 ± 1^{b}	13.9 ± 1.5^{a}
DL_B	39 ± 1^{b}	21 ± 1^{b}	2.6 ± 0.2^{b}	n.r.	n.r.	n.r.	24 ± 0^{b}	14.3 ± 0.6^{a}
	N							
TS_H	1.6 ± 0.1^{a}	0.03 ± 0^{a}	0.21 ± 0.01^{a}	0.28 ± 0.06^{a}	1.43 ± 0.09^{a}	1.37 ± 0.06^{a}	1.4 ± 0.1^{a}	1.17 ± 0.09^{a}
DL_H	1.8 ± 0.1^{a}	0.21 ± 0.02^{b}	0.3 ± 0.02^{a}	0.3 ± 0.05^{a}	1.49 ± 0.13^{a}	1.49 ± 0.1^{a}	1.7 ± 0.1^{b}	1.19 ± 0.11^{a}
DL_B	2.4 ± 0.1^{b}	0.34 ± 0.03^{b}	0.54 ± 0.03^{b}	1.01 ± 0.09^{b}	1.84 ± 0.06^{b}	1.37 ± 0.05^{a}	1.7 ± 0.1^{b}	1.16 ± 0.05^{a}
	K							
TS_H	1.6 ± 0.1^{ab}	0.05 ± 0.01^{a}	0.016 ± 0.001^{a}	0.01 ± 0.05^{a}	1.55 ± 0.12^{ab}	1.55 ± 0.14^{a}	1.6 ± 0.1^{a}	1.46 ± 0.12^{ab}
DL_H	1.8 ± 0.1^{a}	0.44 ± 0.06^{b}	0.024 ± 0.001^{a}	0.197 ± 0.033^{b}	1.82 ± 0.09^{a}	1.65 ± 0.1^{a}	2.1 ± 0.1^{b}	1.77 ± 0.11^{a}
DL_B	1.4 ± 0.1^{b}	0.25 ± 0.01^{b}	0.043 ± 0.003^{b}	0.294 ± 0.054^{b}	1.35 ± 0.06^{b}	1.1 ± 0.08^{b}	1.4 ± 0.1^{a}	1.33 ± 0.07^{b}
	P							
TS_H	0.32 ± 0.02^{a}	0.004 ± 0^{a}	0.079 ± 0.005^{a}	0.096 ± 0.015^{a}	0.24 ± 0.02^{a}	0.22 ± 0.02^{a}	0.22 ± 0.02^{a}	0.23 ± 0.02^{a}
DL_H	0.35 ± 0.04^{a}	0.032 ± 0.005^{b}	0.113 ± 0.007^{a}	0.112 ± 0.011^{a}	0.23 ± 0.03^{a}	0.24 ± 0.03^{a}	0.27 ± 0.03^{a}	0.27 ± 0.03^{a}
DL_B	0.39 ± 0.01^{a}	0.046 ± 0.005^{b}	0.208 ± 0.013^{b}	0.205 ± 0.009^{b}	0.18 ± 0.02^{a}	0.18 ± 0.02^{a}	0.23 ± 0.02^{a}	0.25 ± 0.02^{a}

TS_H compared to the two other treatment groups (Table 3). DL_B intakes differed significantly from DL_H and TS_H only for N. However, according to observed performances, cattle weight and feeding models used, the levels of protein available in the small intestine supply to cattle were very similar in all treatment groups. Indeed DVEr, were 1.31 ± 0.1, 1.30 ± 0.14 and 1.29 ± 0.07 for TS_H, DL_H and DL_B respectively, indicating, on average, a similar ($p > 0.05$) surplus in protein available in the small intestine supply. For K, TS_H had intermediate intake such as DL_H for ash. Globally, except for K, even if not always significant TS_H had a lower nutrient intake than DL treatment groups.

As described in Table 3, the straw supplies for bedding in DL were similar (H: 35 ± 3 and B: 44 ± 2 g DM kg^{-1} mw d^{-1}, $p > 0.05$) and, on average, 8.0 ± 1 times higher than in TS_H ($p < 0.05$). To investigate the barn effect, it is interesting to notice that the total inputs (ingested + litter) per kg of mw were 46 %, 41 %, 47 %, 20 %, 42 % and 18% higher in DL_H than in TS_H for DM, ash, C, N, K and P respectively. On average, 79 %, 63 %, 80 %, 55 %, 59 % and 48 % of these differences were due to straw supply.

3.2.2. Barn output (Out1)

3.2.2.1. Nutrients and C distribution. Whatever the treatment, more than 90 % of the carbon remaining in the system (sum of all measured compartments) was in the deep litter or semi-solid manure (Fig. 2). In TS_H treatment, large proportions of ash (21 ± 1 %), K (38 ± 1 %) and N (16 ± 1 %) were in the liquid fraction of manure collected in barns. Conversely, P and C were marginally present in this fraction (1.7 ± 1 % and 3.0 ± 1 %, respectively). From 26 ± 1 % (TS_H) to 46 ± 1 % (DL_B) of the P and 13 ± 1 % (TS_H) to 24 ± 1 % (DL_B) of the N at Out1 were in the cattle lwg as calculated with referential lw nutrient concentration.

3.2.2.2. Excretion, manure production and characteristics. Literature based estimations of ash, N, P and K excretion by cattle, per kg mw d^{-1} (equation 4; Fig. 2), were similar ($p > 0.05$) for heifers raised in TS and DL. Except for P, the excretion of these nutrients differed between bulls and heifers ($p < 0.05$). Cattle excretion calculated by the difference between manure production and straw supply (Equation 6, Fig. 1) led, on average, to similar ($p > 0.05$) amounts of ash, K and P excretions for TS_H as well as for ash and P for DL_H and P for DL_B compared to the literature based estimation of excretion (equation 4;

Table 4
Manure characteristics (mean ± sem).

		Production (g FM kg^{-1} mw d^{-1})	pH	C/N	DM (g kg^{-1} FM)	C (g kg^{-1} DM)	N	TAN	Ash	K	P
Out1											
SSM or DLM	TS_H	193 ± 4[a]	8.2 ± 0.1[a]	13.7 ± 0.6[a]	179 ± 7[a]	433 ± 3[a]	32.8 ± 1.0[a]	7.8 ± 0.7[a]	148 ± 7[a]	29 ± 3[ab]	6.4 ± 0.4[a]
	DL_H	238 ± 10[b]	7.4 ± 0.3[b]	16.2 ± 0.7[b]	253 ± 6[b]	435 ± 2[a]	27.9 ± 0.7[b]	4.4 ± 0.4[b]	144 ± 4[a]	35 ± 2[a]	4.3 ± 0.3[b]
	DL_B	213 ± 4a[b]	8.4 ± 0.1[a]	14.4 ± 0.4[ab]	262 ± 5[b]	433 ± 2[a]	30.7 ± 0.8[ab]	6.4 ± 0.3[ab]	148 ± 4[a]	24 ± 1[b]	4.1 ± 0.3[b]
LF	TS_H	42 ± 5	8.9 ± 0.1	2.3 ± 0.4	47 ± 2	250 ± 12	144.4 ± 23.8	112.7 ± 18.2	720 ± 13	310 ± 11	3.3 ± 1.2
Out2											
SSM or DLM	TS_H	139 ± 7[a]	7.8 ± 0.1[a]	14.1 ± 0.4[a]	185 ± 7[a]	423 ± 4[a]	30.8 ± 0.6[a]	4.6 ± 0.5[a]	167 ± 8[a]	21 ± 2[a]	8.8 ± 0.3[a]
	DL_H	173 ± 15[a]	8.4 ± 0.1[b]	12.1 ± 0.4[b]	210 ± 16[a]	383 ± 7[b]	32.8 ± 0.8[a]	2.3 ± 0.6[b]	245 ± 14[b]	46 ± 2[b]	7.6 ± 0.3[ab]
	DL_B	157 ± 8[a]	8.5 ± 0.1[b]	13.0 ± 0.5[ab]	238 ± 21[a]	390 ± 5[b]	31.2 ± 1.3[a]	1.2 ± 0.3[b]	233 ± 10[b]	31 ± 2[c]	6.8 ± 0.5[b]
LF	TS_H	210 ± 35[a]	7.9 ± 0.1[a]	5.4 ± 0.9[a]	8 ± 1[a]	279 ± 9[a]	65.5 ± 8.3[a]	27.1 ± 6.5[a]	688 ± 10[a]	210 ± 13[a]	8.4 ± 0.9[a]
	DL_H	54 ± 10[b]	8.3 ± 0.1[b]	5.5 ± 0.6[a]	16 ± 3[b]	237 ± 11[b]	49.2 ± 4.8[a]	14.9 ± 4.1[ab]	735 ± 13[b]	266 ± 4[b]	6.4 ± 0.9[a]
	DL_B	108 ± 26[b]	8.1 ± 0.1[ab]	5.6 ± 0.5[a]	9 ± 1[a]	235 ± 7[b]	45.6 ± 3.8[a]	9.5 ± 1.4[b]	737 ± 7[b]	228 ± 7[a]	6.8 ± 0.7[a]

SSM, semi-solid manure; DLM, deep litter manure ; LF, liquid fraction; TAN, total amoniacal nitrogen; FM, fresh matter; DM, dry matter. For signification of Out1 and Out2, see Fig. 1.

Fig. 1). Significant ($p < 0.05$) less excretions were observed for K in DL_H and DL_B as well as for ash in DL_H when calculated compared to estimated ones (Table 3, statistics not shown).

More manure (i.e. SSM for TS_H and DLM for DL_H and DL_B) was produced in the barn and then stored (Out1) on concrete facilities for DL (58 ± 2 g DM kg^{-1} mw d^{-1}) treatments compared to TS_H (34 ± 1 g DM kg^{-1} mw d^{-1}). Higher amounts of ($p < 0.05$) ash, C and N were in DLM than in SSM; higher quantity of K in DLM of DL_H compared to DLM of DL_B and SSM of TS_H while no difference was recorded for P ($p > 0.05$).

DL's manure also had higher DM and lower P and N concentrations ($p < 0.05$, Table 4). Total ammoniacal nitrogen (TAN) was higher ($p < 0.05$) in TS_H compared to DL_H while it was intermediate for DL_B. The pH of DL_H was lower ($p < 0.05$) than the pH of the manure obtained in the two other treatments. Potassium was more concentrated in DL_H manure ($p < 0.05$) than in DL_B manure. TS_H had intermediate values.

3.2.2.3. Losses at barn. According to mass balances (Table 5), significant losses, as a proportion of the inputs at Out1, were observed for C for all treatment groups. Carbon losses, as a proportion of inputs, were significantly higher for TS_H (56.2 ± 1.6 %) and DL_B (54.9 ± 0.9 %) than for DL_H (49.7 ± 1.5 %). A significant proportion of K entering the system was missing for DL_H and DL_B (respectively 7.6 ± 1.3 % and 15.4 ± 3.1 %). Some N was also lost (significantly different from zero) for DL_B (16.8 ± 2.5%) but not for the two other treatment groups. Whatever the treatment, no significant losses were observed for P and ash.

3.2.3. After manure storage (Out2)

3.2.3.1. Nutrients and C distribution. On average, more than 80 % of the C remaining in the system at Out2 was in the deep litter or semi-solid manure (Fig. 2). From 1 % to 7 % were found in the liquid fraction collected at the barn and storage. Conversely, large proportions of ash and K were in the liquid fraction ranging from around 6 % in DL_H to 35 % in TS_H for ash and 10% in DL_H to 63 % in TS_H for K. In TS_H, on average, 27 % of the N, at Out2, were in the liquid fractions this proportion is only of 2–3 % in DL systems. Solid manure contained from 57 % to 77 % of the N left in the systems with the lower proportion for TS_H. It was estimated that 26 %–46 % of P were in the animal gains while less than 5.5 % were in the liquid fractions.

3.2.3.2. Manure production and characteristics. After storage (Out2, Table 3) similar amounts ($p < 0.05$) of C (from 11.9 ± 0.8 to 14.3 ± 0.6 g kg^{-1} mw d^{-1}), N (from 1.16 ± 0.09 to 1.19 ± 0.05 g kg^{-1} mw d^{-1}) and P (from 0.23 ± 0.02 to 0.27 ± 0.03 g kg^{-1} mw d^{-1}) were in the manure for all treatment groups. There was significantly ($p < 0.05$) more ash in DL systems (DL_H: 9.0 ± 0.6, DL_B: 9.1 ± 0.5 g kg^{-1} mw d^{-1}) compared to TS_H (6.7 ± 0.3 g kg^{-1} mw d^{-1}). Significantly more K was produced in DL_H (1.77 ± 0.11 g kg^{-1} mw d^{-1}) compared to DL_B (1.33 ± 0.07 g kg^{-1} mw d^{-1}), while it was intermediate for TS_H (1.46 ± 0.12 g kg^{-1} mw d^{-1}).

Concerning SSM and DLM after storage (Table 4), for fresh matter production (154 ± 5 g FM kg^{-1} mw d^{-1}), dry matter concentration (209 ± 9 g DM kg^{-1} FM), and N concentration (31.4 ± 0.5 g N kg^{-1} DM), there were no significant differences between treatments. C concentration and TAN were lower in DLM compared to SSM while for pH, K and ash it is the opposite (Table 4). P concentration of DL_H solid manure were similar to those of the solid and semi-solid manures of the others treatment groups while these two last (TS_H and DL_H) significantly differ for this parameter. C/N ratio of solid and semi-solid manures of TS_H and DL_H differed significantly ($p < 0.05$) but were both similar to C/N ratio in DL_B solid manure.

3.2.3.3. Losses at the term of the storage period. From 65.6 % to 72.3 % of the total C input, 8.7 %–20.8 % of K and 17.2 %–37 % of N were lost ($p < 0.05$) at Out2 (Table 5). Significant gains of ash (6.3 %) were observed for TS_H while for the DL_H (gain of 3.0 %) and DL_B (0.1 %) balances were not different from 0 ($p > 0.05$). There were no differences between treatments in losses as a proportion of total input of C while N losses were significantly higher for DL_B (37 %) compared to TS_H (17.2 %) and DL_H (26 %). Less K was lost in TS_H (8.7 %) compared to DL_H (20.8 %) and DL_B (17.0 %). However when related to ingestion, losses of C and N where significantly higher (respectively +52 % and +103 %) in DL systems compared to TS_H. Comparison of losses at Out1 and at Out2, shows that N is mainly lost during SSM and DLM manure storage. Those losses amount to about 20 % of the N stored in the TS system (Table 4) and it is significantly different to the proportion of N losses in the DL system (about 30 %). Similarly, proportions of C losses are around 2 times lower in TS_H than in DL systems during SSM and DLM storage. C and N losses on a daily basis, during manure storage, were strongly correlated (Fig. 3): N losses (% of N stored d^{-1}) = 0.038 + 0.617*C losses (% of C stored d^{-1}); $p < 0.001$ and $r^2 = 0.787$.

Over the whole system, the variability in the proportion of N losses (i.e. at Out2 and expressed in % of N input) were positively correlated ($p < 0.05$) with both storage duration, temperature over the storage period and STRAWr. DVEr was not significantly ($p > 0.05$) correlated to the proportion (%) of total N lost and weakly improved the relation (r^2adjust with DVEr = 0.550; without DVEr = 0.534) while N concentration in feed was correlated ($p < 0.01$) to N losses and improved

Table 5
Losses calculated according to mass balance of the nutrient at the different stages in function of the barn type and the unit. Values within brackets do not differ from 0.

		In (%)	Ingested (%)	Excreted (%)	Gain (g kg^{-1})	mw (10^{-5} kg kg^{-1})	Stored (%)
		Ash					
Out1	TS_H	(-3.4 ± 3.2)^{a}	(-3.5 ± 3.3)^{a}	(-3.6 ± 3.4)^{a}	(-45.3 ± 32.8)^{a}	(-22.7 ± 19.8)^{a}	
	DL_H	(0.3 ± 2.1)^{ab}	(0.7 ± 2.7)^{ab}	(0.7 ± 2.8)^{ab}	(5.4 ± 21.2)^{a}	(-0.2 ± 19.5)^{ab}	
	DL_B	(8.1 ± 3.6)^{b}	(10 ± 4.6)^{b}	(10.9 ± 5)^{b}	(44.7 ± 21.8)^{a}	(89.8 ± 39.7)^{b}	
Out2	TS_H	−6.3 ± 2.3^{a}	−6.5 ± 2.4^{a}	−6.8 ± 2.5^{a}	−75.7 ± 27.9^{a}	−42 ± 15.5^{a}	(-4.2 ± 2.8)^{a}
	DL_H	(-3 ± 4.2)^{a}	(-3.5 ± 5.7)^{a}	(-3.8 ± 6)^{a}	(-21 ± 44.2)^{a}	(-25 ± 37.8)^{a}	(-3.7 ± 4.8)^{a}
	DL_B	(0.1 ± 3.8)^{a}	(-0.5 ± 4.8)^{a}	(-0.5 ± 5.2)^{a}	(-3.2 ± 23.4)^{a}	(8.9 ± 41.2)^{a}	−10 ± 4.1^{a}
		C					
Out1	TS_H	56.2 ± 1.6^{a}	59.5 ± 1.6^{a}	61.3 ± 1.7^{a}	3332.7 ± 213.2^{a}	2111.1 ± 72.6^{a}	
	DL_H	49.7 ± 1.5^{b}	70.1 ± 2.9^{b}	72.9 ± 2.9^{b}	2992.5 ± 266^{a}	2735.4 ± 127.4^{b}	
	DL_B	54.9 ± 0.9^{a}	84.1 ± 2^{c}	90.1 ± 2.1^{c}	1952.6 ± 131.5^{b}	3272.3 ± 111.5^{c}	
Out2	TS_H	65.6 ± 2.1^{a}	69.6 ± 2.5^{a}	71.7 ± 2.5^{a}	3880.3 ± 227^{a}	2460.4 ± 80.3^{a}	22.4 ± 5.5^{a}
	DL_H	72.3 ± 2.5^{a}	102 ± 3.9^{b}	105.9 ± 3.8^{b}	4366.8 ± 392.1^{a}	3977.4 ± 176.9^{b}	47.7 ± 4.6^{b}
	DL_B	71.5 ± 1^{a}	109.6 ± 2.8^{b}	117.4 ± 2.8^{c}	2549.1 ± 185.6^{b}	4255.1 ± 121.9^{b}	40.5 ± 3^{b}
		N					
Out1	TS_H	(2.8 ± 2.9)^{a}	(2.8 ± 3.0)^{a}	(3.2 ± 3.4)^{a}	(8.1 ± 7.9)^{ab}	(6.6 ± 5.2)^{a}	
	DL_H	(-0.6 ± 2.4)^{a}	(-0.7 ± 2.7)^{a}	(-1 ± 3.3)^{a}	(-0.4 ± 4.9)^{a}	(0.6 ± 4.1)^{a}	
	DL_B	16.8 ± 2.5^{b}	19.2 ± 2.8^{b}	24.8 ± 3.6^{b}	27.4 ± 4.4^{b}	46.8 ± 7.7^{b}	
Out2	TS_H	17.2 ± 3.1^{a}	17.5 ± 3.1^{a}	20.3 ± 3.7^{a}	42.9 ± 7.2^{a}	28.7 ± 5.2^{a}	20.1 ± 3.3^{a}
	DL_H	26 ± 1.4^{a}	29.1 ± 1.5^{b}	35 ± 1.8^{b}	55.1 ± 4^{a}	51.2 ± 3.5^{b}	30.8 ± 2.8^{b}
	DL_B	37 ± 2.2^{b}	42.3 ± 2.5^{c}	54.6 ± 3^{c}	60.7 ± 5.6^{a}	101.8 ± 8.1^{c}	31.9 ± 2.1^{b}
		K					
Out1	TS_H	(-0.1 ± 2.8)^{a}	(-0.1 ± 2.9)^{a}	(-0.1 ± 2.9)^{a}	(-2.2 ± 9.2)^{a}	(-0.6 ± 5)^{a}	
	DL_H	7.6 ± 1.3^{ab}	9.7 ± 1.8^{ab}	9.8 ± 1.8^{ab}	19.4 ± 4.4^{a}	17.3 ± 3.3^{b}	
	DL_B	15.4 ± 3.1^{b}	18.2 ± 3.7^{b}	18.8 ± 3.8^{b}	15.1 ± 3.3^{a}	25.1 ± 5.4^{b}	
Out2	TS_H	8.7 ± 2.4^{a}	9 ± 2.5^{a}	9.1 ± 2.5^{a}	22.5 ± 6.4^{a}	13.8 ± 3.9^{a}	13.8 ± 3.3^{a}
	DL_H	20.8 ± 4.3^{b}	26.3 ± 5.9^{b}	26.6 ± 6^{b}	56.2 ± 16.7^{b}	49.3 ± 12.5^{b}	14.4 ± 4.6^{a}
	DL_B	17 ± 2.7^{ab}	20.2 ± 3.2^{ab}	20.8 ± 3.3^{ab}	16.5 ± 2.6^{a}	27.6 ± 4.2^{ab}	(0.7 ± 5.5)^{a}
		P					
Out1	TS_H	(3.9 ± 3.7)^{a}	(3.9 ± 3.7)^{a}	(4.8 ± 4.9)^{a}	(2.6 ± 2.1)^{a}	(1.7 ± 1.3)^{a}	
	DL_H	(-0.9 ± 2.1)^{a}	(-1 ± 2.3)^{a}	(-2 ± 3.5)^{a}	(-0.2 ± 0.9)^{a}	(-0.2 ± 0.8)^{a}	
	DL_B	(-1.4 ± 3)^{a}	(-1.4 ± 3.3)^{a}	(-14.5 ± 14.1)^{a}	(0.1 ± 0.7)^{a}	(-0.3 ± 1.3)^{a}	
Out2	TS_H	(2.9 ± 2.4)^{a}	(2.9 ± 2.4)^{a}	(3.8 ± 3.2)^{a}	(1.6 ± 1.2)^{a}	(1.1 ± 0.8)^{a}	(-2.9 ± 4.4)^{a}
	DL_H	(-3.8 ± 4.3)^{a}	(-4.3 ± 4.8)^{a}	(-8 ± 8.2)^{a}	(-1 ± 1.4)^{a}	(-0.7 ± 1.2)^{a}	(-4.6 ± 4.8)^{a}
	DL_B	(-6.4 ± 3.5)^{a}	(-7 ± 3.9)^{a}	(-29 ± 16.2)^{a}	(-1.1 ± 0.7)^{a}	(-2.6 ± 1.5)^{a}	(-10.9 ± 6)^{a}

For signification of in Out1 and Out2, see Fig. 1. Mw, metabolic weight.

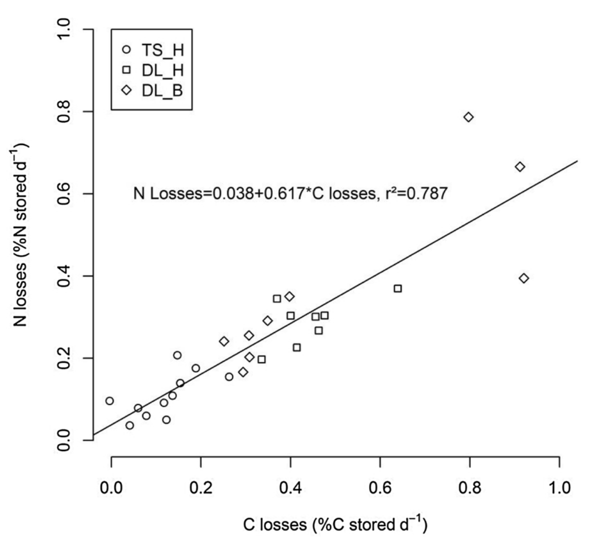


Fig. 3. Relation between carbon and nitrogen losses, both expressed as % of amount stored in manures. TS_H, DL_H and DL_B refer to manures produced respectively in tied stalls by heifers, deep litter stalls by heifers and deep litter stalls by bulls (n = 28, one dataset, trial 26, was discarded after outlier identification).

the relation to obtain: % total N loss = −33.33 + 0.0869*storage duration + 1.11*storage temperature + 27.9*STRAWr + 1.278*NFEED; r^2 = 0.700.

4. Discussion

4.1. Cattle live weight gain composition reference values and balances (losses)

The total and barn balances calculation was a mix between the use of referential values, through nutrients immobilized in cattle live weight gains, and measured data (weight and analysis). The reference values for nutrients fixed by cattle may introduce a bias in balance mainly for P due to the large variation of fixation levels recorded in the literature. However, while P concentration estimated in cattle live weight gain was similar to the high value found in the literature (12 g P kg^{-1} lw), without divergence between treatment groups, variations were observed for K with higher values in DL systems. Those observations are consistent with not zero K balance at Out1 and Out2 and their interaction with barn type.

4.2. K, P and ash balances and indicators for C and N balances

Contrasts in K balances with treatment at the barn (Out1) and manure storage (Out2) phases were observed and many hypotheses can be found to explain K unbalances such as bias in weighing, in concentration determinations, in sampling, in analytical procedures, etc. These contrasts, furthermore, raise uncertainty about the distribution and losses of other nutrients like N, C and P of the systems studied. To verify the validity of the N balances observed, a correction was tested in two steps each relying on, to our opinion, the most reliable hypothesis regarding expertise and controlled procedures. The first step is based on the assumption that the main reason leading to the no zero K balance was bias in their amount in SSM and DLM due to an inadequate sampling procedure or sample preparation before analysis (mineralization, etc.). The choice of this assumption relies partially on the fact that there was no evidence of liquid fraction losses from manure at barn and that heterogeneity in feed sampling is supposed to be weak compared to those of SSM and DLM. Furthermore, considering heterogeneity in manure composition due to straw supply and a potential gradient in concentration, mainly for mobile elements like K, it is difficult to take a representative sample in solid manure. Therefore, N losses at Out1 were corrected according to the positive and significant ($p < 0.05$, $n = 29$) but weak ($r^2 = 0.232$) relation between K and N losses (% of input) at Out1. The second step relied on field observations indicating K losses during storage due to uncollected liquid fraction (estimated at 13 ± 31 % of K collected in liquid fraction) because of not optimized liquid fraction collecting system. Therefore, losses of N in storage were corrected considering that the K losses, after correction of losses in the barn at the first step, were due to losses of the liquid fraction in storage. N losses during SSM and DLM storage were thus corrected by subtracting the supposed amount of N lost in the uncollected liquid fraction. Those calculations led to estimations of N losses of 2.9 ± 3.4 %, −4.5 ± 2.5 % and 9.0 ± 1.5 % of the N input for TS_H, DL_H and DL_B respectively at Out1 and losses of 11.7 ± 3.8, 27.8 ± 3.0 and 27.9 ± 2.0% respectively of the N input at Out2. Losses were significantly different from zero ($p < 0.05$) only for DL_B at Out1 but for all treatments at Out2. At Out2, N losses from TS_H were significantly different from that observed for DL_H and DL_B which do not differ. These last observations confirm that a significant contrast exists between N losses among barn types.

According to legislation of Walloon region (Belgium) (AGW, 2014), manure from DL systems can be stored for a maximum duration of 10 months on land without liquid fraction collection. However, considering the amount of K in SSM and DLM after storage, K losses during such storage can be important and highly variable. Indeed, as observed they ranged from 0.02 to 0.59 % of K stored, per day of storage, with an average value of 0.24 ± 0.02 % across treatments, without significant differences between them. Chadwick (2005) observed losses ranging from 0.22 to 0.54 % of K stored, per day, for beef farmyard manure. These variations in the total proportion of K stored lost were mainly related to rainfall during storage (Fig. 4). According to this relation and to an average precipitation level of 800 mm year^{-1} (IRM, 2014), losses of 41 % of K can be expected after 10 months of storage with 5 % after 1 month. Losses of P were far less problematic because they were not significant (0.01 ± 0.02 % of P stored d^{-1}) and independent of rainfalls and barn or cattle types.

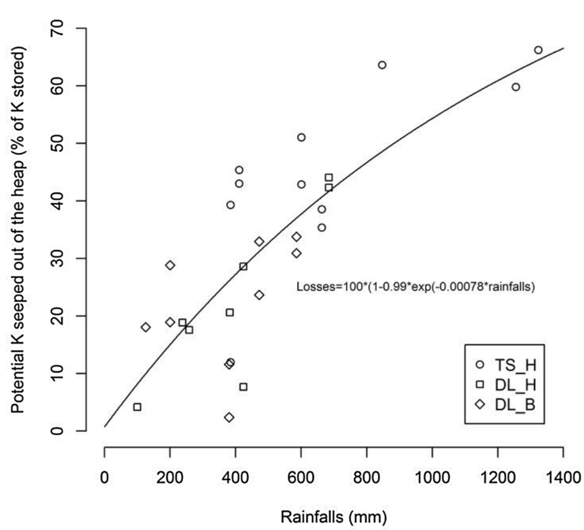


Fig. 4. Relation between potential K losses (% of stored) at storage (liquid fraction + losses) and rainfall (n = 28, one dataset, trial 26, was discarded after outlier identification).

4.3. N and C losses: functional units, treatment and manure management effects

Nitrogen losses at Out1 were very variable and not different from 0 for TS_H and DL_H whereas N-NH_3 losses at a rates of 0.16–0.32 g N kg^{-1} mw d^{-1} could have been expected for beef cattle according to Misselbrook et al. (2000), indicating potential underestimation of N losses in the barn for TS-H and DL-H. Considering that variation in nitrogen concentration in feed can induce strong change of N fluxes at cattle level (Dijkstra et al., 2013) and consequently potentially large modification in losses, notably as volatile compounds (ammonia) after excretion (e.g. Misselbrook et al., 2005; Webb et al., 2012), difference in N concentration in feed between treatments can lead to confusion of effects, notably with barn or cattle type. In this respect, higher N losses in the barn for DL_B can be explained by higher DVE concentration in feed compared to DL_H and TS_H, potentially leading to higher N emissions as N-NH_3. This is confirmed by the relation between DVE concentration in feed and the proportion of N lost (%) in the barn ($p < 0.01$; N lost barn (% of N input) = 0.7*DVE (g kg^{-1} DM feed) - 44.24). However, the relation observed is partially in contradiction with the results reported at point 3.2.1.2 showing that the protein supply to cattle requirement ratio was, on average, similar for TS_H, DL_H and DL_B. Webb et al (2012) also suggested that emissions of N as ammonia and thus N losses were higher in TS compared to DL due to the variation of emitting area size. In our trial, emitting area per head of cattle was estimated to be 50 % higher in DL compared to TS while losses were very similar and not different from zero. Finally, we cannot exclude that nutrition model used underestimate DVE requirements for heifer, and that, in practice, cattle DVE nutrition levels were optimal resulting in low N excess and consequently low N gaseous emissions at the barn.

Losses during manure storage ranged from 5 to 42 % of the N stored and were similar to already reported values (Chadwick, 2005; Moral et al., 2012; Petersen et al., 1998). Independently of the unit used (nitrogen input, nitrogen ingested by cattle or to cattle production), nitrogen losses, even if corrected for K losses (not shown), were ranked as follow DL_B > DL_H > TS_H (Table 5) meaning that TS was always more efficient in keeping nitrogen in the system compared to DL systems. These observations are consistent with the fact that (1) losses (supposed as nutrient gaseous emission) occurred mainly during manure storage and (2) that manure from the deep litter system has a lower density (DL = 0.5 to 0.82 t fresh matter m^{-3}, TS > 0.9 t fresh matter m^{-3}; Mathot et al., 2012 and 2016) inducing self-heating processes and high decomposition rate of organic matter (Webb et al., 2012) with, consequently, high level of gaseous emissions. In our opinion, the best unit to compare these systems would be the “N ingested” that refers to similar production potential for a given animal type. According to this choice, there is a higher N input (straw) in DL systems compared to TS and far more N losses.

Contrary to nitrogen, carbon losses occurred mainly in the barn (C losses at Out1; Table 4) and then at manure storage. At barn, they corresponded to estimations of direct cattle emission (61.9 ± 1, 51.1 ± 1 and 46.1 ± 1 % of the C input of the system for TS_H, DL_H and DL_B respectively), calculated by the difference of organic matter digestibility (expressed in C) and C in cattle lwg. At manure storage, C losses varied considerably between systems from less than 5 % to 65 % of the C stored with an average of 36.3 ± 3 %. Similar amounts have been observed in the literature (e.g. 38–46 %; Chadwick, 2005). These variable losses lead, for all systems, to very similar N and C remaining per kg of cattle mw amounts at Out2 in manure. This led us to the conclusion that despite a large variation in inputs, after storage, the remaining carbon and nitrogen in the manure were independent of the barn type.

It was found that the level of N losses (i.e. at Out2 and expressed in

% of N input) was linearly related to manure storage duration, ambient temperature over the storage period, straw supply level and N concentration in feed. However the assumption of linear relation between nitrogen losses and storage duration should be carefully interpreted and certainly not extrapolated to lower storage duration (in this trial 49 days) due to high and fluctuating N-NH_3 emission rates within the first weeks of manure storage as already reported elsewhere (Chadwick, 2005). According to the relation defined, within the ranges studied (from minimum to maximum values) variation in storage duration (49–278 d), temperature over the storage period (0.18–16 °C), STRAWr (0.04–0.64 kg DM straw kg^{-1} DM feed ingested) and NFEED (15.6–28.7 g N kg^{-1} DM) induce an increase of 20, 18, 17, 17 and 18 of % N losses. Therefore, in the experimental conditions of these trials, we conclude that losses of nitrogen were driven to a similar extent by cattle nitrogen feeding parameters, storage duration and conditions and barn types as expressed by STRAWr.

4.4. Manure management, agronomic and environmental implications

Despite some uncertainty about nutrient balances, the relation observed between nutrient losses and management parameters can help in optimizing nutrient flows and availability from cattle's mouth to manure ready for application in TS and DL systems. However, for C and N, they give no indication about the type of molecules lost and their potential environmental impact. Indeed, losses may occur under different molecules for N (mainly N_2, N_2O and NH_3) as for C (mainly CO_2 and CH_4) during farmyard manure storage. Furthermore, parameters such as manure density, rainfall and temperature evolve spatially and in temporally, influencing, among others, oxygen availability in the heap and finally the type and rate of gaseous compounds emitted. According to Webb et al. (2012), an increase in emission of ammonia can be expected from manures with a decrease in solid manure density during storage. This density typically decreases with straw supply and ammonia is mainly emitted within the first 21 days of storage (e.g. Külling et al., 2003; Petersen et al., 1998; Moral et al., 2012). Therefore, we can suppose that manure with the highest straw supply and the related highest nitrogen losses would have the highest NH_3 emissions. For N_2O, observations from Mathot et al. (2012, 2016) on some of the manure considered in this study indicated that the highest N_2O emission were observed for the manure with the highest N losses. Those results do not agree with the general trend showed by Webb et al. (2012) where nitrous oxide emissions rate (% of N stored) increase with manure density. However, the density observed during storage, in our trials, were typically between the 0.5 and 0.9 t m^{-3} (Mathot et al., 2012 and 2016), range in which the nitrous oxide emissions are very variable for a given density. Concerning C losses, as reported by Mathot et al. (2012) and (2016) methane and carbon dioxide emissions were by far lower for the manures with the highest densities. Those results were explained by (1) the low temperature occurring within these manure piles as these trials were mainly carried out during the winter period and (2) the very high density of the manure due to low straw supply that limit degradation of the organic matter and consequent gaseous emissions. Thus, according to the gaseous emissions measurement for some of the trials, a higher environmental impact in terms of greenhouse gas emissions can be expected form DL compared to TS manures.

The cases investigated included two main manure types that are also produced in other barn types than tied stall and deep litter. The figure and relations found could thus potentially be used for a wide range of barn systems. For example, scraped areas lead to production of semi-solid manure similar to the manure produced in tied stalls. However, the observation of variations in nutrient transmission efficiency from system inputs to manure available for fertilization should be interpreted carefully, even more when considering potential gaseous emissions and manure agronomical value. Indeed, as illustrated by Sommer and Møller (2000) for pig manure, change in manure management, like variation in straw amount supply to reduce manure density (0.44–0.23 t FM m^{-3}), out of the range of the values reported in our trials with gaseous emissions measurements (> 0.5 t FM m^{-3}), decreased gaseous emissions by the manure heaps. Furthermore, for example, semi-solid manure does not induce a self-heating process due to its low porosity and thus prevents beneficial effect of such self-heating process (weed seeds destruction, pathogens destruction, etc.; Larney and Hao, 2007) and, in this way, may reduce the agronomic quality of the manure. Therefore, changes in manure type have to be considered carefully.

Finally, these results illustrate the complexity of modelling nutrient flows and losses from manures based on experimental trials regarding the existing diversity due to regional management and variations in climatic conditions. In the future, according to the results presented and within the manure management systems described, modelling of nutrient flows related to SSM and DLM can be developed to characterize the impact of contrasted management schemes on nutrient losses to the environment. Indeed, at least for nitrogen and potassium, relations between losses and some management parameters such as storage duration and storage conditions (rainfall, temperature) may help in keeping nutrients one step further along the manure management continuum to sustain nutrient recycling and cattle-based system fertility.

5. Conclusion

Managing nutrients in livestock-based systems is of major economic and environmental importance for keeping fertility and avoiding emissions of damaging molecules into the environment. Among the manure management continuum, barn and storage phases have to be optimized according to identified influencing factors such as barn type, cattle feeding, manure storage duration and climatic conditions. At least limiting manure storage duration may reduce losses of nutrients that, in the case of potassium for example, are related to the amount of rainfall falling on the manure. In the future, for similar manure production and storage conditions, the developed models could be used as tools to investigate better manure management practices in accordance with crop production requirements. However, major modifications such as changing barn type, and thus manure type, or manure management, like straw amount as litter, have to be considered carefully regarding their agronomical (cattle health and welfare, pathogens destruction, ease of manure application to land, etc.) and their global environmental (greenhouse gas emission, etc.) consequences.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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