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Interactions between nitrogen release from organic fertilisers and organic horticultural soils

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ABSTRACT
Mushroom compost has been one of the most commonly used fertilisers in organic greenhouse vegetable production in Iceland. However, mushroom compost contains conventional chicken manure. Therefore, the use of this fertiliser is prohibited in organic horticulture. In search of alternative nutrient resources, nine different substitutes for mushroom compost (plant compost, four composted animal manures, fishmeal, white clover residues, coarse meal of faba beans, 'Pioner complete 6-1-3®') were tested on two soils differing in organic matter in a pot experiment. Dry matter yield (DM) and the apparent N utilisation with the model plant perennial ryegrass was quantified in five cuts throughout 131 days. Both the DM yield and the apparent N utilisation was influenced by the fertiliser, the soil and their interaction. The N release of the tested alternative organic fertiliser resources was described by the N content and C:N ratio of the fertilisers, but was also affected by the soil. It was concluded that the composted animal manures provided an N release equal to mushroom compost and could therefore act as substitutes.

Keywords: C to organic N ratio; N content; nitrogen release; organic farming; organic fertiliser

YFIRLIT
Samspil köfnunarefnislosunar frá lífrænum áburði og lífrænum ylræktarjarðvegi
Sveppamassi hefur verið einn mest notaði áburður í lífrænni grænmetisframleiðslu á Íslandi. Hins vegar, þar sem hann inniheldur hænsnaskít sem ekki er lífrænt vottaður, er notkun þessa áburðar bönnuð í lífrænni garðyrkju. Þess vegna voru aðrar gerðir áburðar í stað sveppamassa (plöntumolta, fjórar mismunandi moltugerðir úr búfjáráburði, fiskimjöli, plöntuleifum af hvítsmára, möluðu fræi af hestabaunum, 'Pioner complete 6-1-3®') prófaðar í pottatilraun í tveimur gerðum af jarðvegi sem voru með mismikið magn af lífrænum efnum. Þurrefnisuppskera og niturnýting með rýgresi var mæld fimm sinnum á 131 dags vaxtartímabili. Bæði, þurrefnisuppskera og niturnýting var undir áhrifum af tegund áburðargjafa, jarðvegs og samspils þeirra. N nýting var lýst með N innihaldi og C:N hlutfalli áburðarins, en var einnig undir áhrifum af jarðvegi. Niðurstaðan var sú að moltan úr búfjáráburði gæfi jafnmikla niturupptöku eins og sveppamassi og gæti því verið notaður í staðinn.

INTRODUCTION
Organic fertilisers and crop residues are important nutrient sources for plants in sustainable crop systems (Whalen et al. 2013). Depending on the origin of the fertiliser, the proportion of N available to plants in organic fertilisers varies greatly (Gutser et al. 2005, Sradnick & Feller 2020). The inorganic N content in organic fertilisers ranges from 0% of

total N in keratin-based fertilisers to 70% and more in liquid organic fertilisers. A considerable part of the N is organically bound. The organic bound N fraction of fertilisers is undergoing microbial decomposition and has to be first mineralised before available for plant uptake in the inorganic form. Different factors can affect N mineralisation, including soil properties (among other things rate of mineralisation of native soil organic matter) as well as the properties of the organic material (Magdoff 1978, Robertson & Groffman 2007). Consequently, the amount of plant-available N from organic fertilisers in the soil varies in the first months after application (Gutser et al. 2005).

In Iceland, mushroom compost was one of the most commonly used fertilisers in organic vegetable production until the end of June 2013. Since July 2013, the use of mushroom compost in organic production was forbidden according to the requirements for organic production set by Council Regulation *(EC) No 834/2007* of 28 June 2007 and implementing regulations (*No 889/2008* and *No 1235/2008*) as it contains conventional chicken manure. Although organic chicken husbandry has been practiced in Iceland since the beginning of 2016 (Hreiðarsson 2016), the conventional chicken manure in mushroom compost has not yet been replaced. Therefore, the exclusion of mushroom compost as a fertiliser in organic horticulture cannot be withdrawn. Thus, suitable substitutes for mushroom compost are required. To date, few studies on organic fertilisers focusing on yield of vegetable crops have been conducted in Iceland. In contrast, many studies focused on the effect of organic fertilisers in other European countries. However, the results of these studies cannot be transferred to Iceland as suitable organic fertilisers are not available in Iceland and the associated import costs are high. In addition, suitable organic fertilisers in European countries might give different results in Iceland. Experiments were mainly conducted with mushroom compost (Gunnlaugsson 1995, Gunnlaugsson 1997), mushroom compost in comparison to fishmeal (Gunnlaugsson & Guðfinnsson 2004) or a mixture of fishmeal and seaweed in comparison to NuGro (liquid fertiliser based on fishmeal) (Stadler et al. 2010). However, additional fertilisers might be suitable for substitution, e.g. horse and sheep manure from organic production or from conventional production after composting or crop residues.

Due to a high N requirement of vegetable crops, N fertilisers used for organic vegetable production should ensure high N turnover, fast N availability, and continuous N supply. Therefore, the prediction of N mineralisation in organic fertilisers is an important tool to optimise organic fertiliser application (Sradnick & Feller 2020). However, due to a lack of information on the amount of plant-available N that is mineralised within the growth period, knowledge to predict the N mineralisation of organic fertilisers is crucial (Sradnick & Feller 2020). Several studies agreed that the C to N or the C to N_{org} ratio of the organic fertiliser – plant residues, manure, mushroom compost – was the main factor influencing the net N release within the first months after application (Trinsoutrot et al. 2000, Kumar et al. 2003, Stadler et al. 2006, Chen et al. 2014). However, as N release depends on soil characteristics (Stadler 2006), it is therefore important to study the net N release from organic fertilisers in different soils.

The aim of this study was to investigate: (1) the effect of composted animal and crop residues, legumes and commercial organic fertilisers on DM yield and apparent N utilisation by ryegrass, (2) whether N release from these fertilisers can be predicted by their N content or C:N ratio, and (3) whether this relation is subject to modification by different soils.

MATERIAL AND METHODS

Fertilisers

Composted animal residues (cow, sheep, horse or chicken manure) from organic production, residues from the fish industry (fishmeal, Síldarvinnslan hf., Neskaupstaður, Iceland), crop residues (plant compost, white clover residues), coarse meal of faba beans (*Vicia faba* L.), the imported industrially processed plant residue 'Pioner complete 6-1-3®' (liquid fertiliser based on sugar beets and sugar cane, Azelis) were investigated in a pot experiment. Mushroom compost (Flúðasveppir ehf., Flúðir, Iceland) was commonly used as a fertiliser in organic vegetable production in Iceland and, therefore, is used as a reference. All kinds of composts were fully composted and mature. In contrast, white clover was cut into small cuttings and mixed while fresh (15.6% DS) into the soil.

Generally, residues with a small particle size showed a stronger and longer N immobilisation and subsequently lower N mineralisation than those with a large particle size (Corbeels et al. 2003). Therefore, to minimise particle size effects so as to better compare the investigated fertilisers, faba beans were coarsely milled and the composted plant and animal residues were sieved to pass through a 5.0 mm screen before chemical analysis.

The selected organic fertilisers show a wide range in N and C content and C:N ratio (Tab. 1). The N content was low in the plant compost (0.9% N), mushroom compost and composted animal manure (1.9-2.6% N). White clover residues, coarse meal of faba beans and Pioner complete 6-1-3® had intermediate values (3.6-5.4% N). The N content (10.9% N) of the commercial organic fertiliser of animal origin, fishmeal, was high. The C content of the investigated organic fertilisers varied considerably. The C:N ratio of composted animal manure, white clover residues and coarse legume meal was high (7.9-17.2). In contrast, the C:N ratio was much lower for Pioner complete 6-1-3® (2.8) and fishmeal (3.9). The P content in relation to the N content was very high for white clover residues (N:P ratio: 21), but relatively low for plant compost (N:P ratio: 2.2). The coarse meal of faba beans (N:P ratio: 7.4), cow compost (N:P ratio: 6) and remaining fertilisers (N:P ratio: 3-5) had medium values. The N:K ratio for all fertilisers was between 1-2, but higher for the coarse meal of faba beans and white clover residues (about 3.5) and for fishmeal (nearly 9).

Soils

Two loess soils (Vitric Andosols according to WRB), differing in the amount of organic matter and total nitrogen (N_t) as well as in the content of P and K, were selected from greenhouses (Tab. 2). The greenhouse soils were obtained

Table 1. N, C, P and K content and C:N, N:P and N:K ratios of the tested organic fertilisers.

Fertiliser	N content* (%)**	C content* (%)**	C:N ratio	P* (%)****	K* (%)****	N:P ratio	N:K ratio
Mushroom compost (reference)	1.91	22.2	11.6	0.44	1.04	4.3	1.8
Plant compost	0.89	10.5	11.8	0.40	0.46	2.2	1.9
Cow compost	1.92	21.7	11.3	0.58	0.89	3.3	2.2
Horse compost	1.98	34.0	17.2	0.54	1.91	3.7	1.0
Sheep compost	2.53	34.6	13.7	0.42	2.68	6.0	0.9
Chicken compost	2.57	20.3	7.9	0.80	1.26	3.2	2.0
White clover residues	3.56	38.5	10.8	0.17	1.05	20.9	3.4
Coarse meal of faba beans	4.29	42.7	10.0	0.58	1.24	7.4	3.5
Pioner complete 6-1-3®	5.40	15.2	2.8	1.25	3.75	4.3	1.4
Fishmeal	10.94	42.7	3.9	2.25	1.24	4.9	8.8

* Values are referring to DM (for 'Pioner compete 6-1-3®' was a fresh sample analysed)

** Chemical analysis according DIN ISO 13878

*** Chemical analysis according to DIN ISO 10694

**** Chemical analysis according to the German fertiliser ordinance (VDLUFA)

Table 2. Characteristics of the greenhouse soils used.

Soil name	C_{org}	N_t	C:N	pH ($CaCl_2$)	P (CAL)	K (CAL)
	(—— %	——)			(mg / 100 g	dry soil)
soil $_{lower\ Corg}$	6.8	0.6	10.7	6.4	27	18
soil $_{higher\ Corg}$	12.8	1.0	13.0	6.5	287	49

from organic vegetable growers from the 0-20 cm soil layer and sieved to pass through a 5.0 mm screen before chemical analysis. Both soils were under organic cultivation for more than 20 years. Soil $_{higher\ Corg}$ regularly received mushroom compost, while soil $_{lower\ Corg}$ received plant compost.

Pot experiment

A pot experiment with ten fertilisers (Tab. 1) and a treatment without fertiliser as a control (Tab. 2) was carried out with two different soils in winter 2012/2013 at the experimental greenhouse facilities of the Agricultural University of Iceland at Reykir, Hveragerði (21°12′W, 64°0′N), South Iceland. The experiment was set up in one greenhouse chamber (60 m^{-2}) which provided computer-controlled optimal microclimate conditions (18 °C / 15 °C (day / night), 240 W m^{-2}). 3.7 kg of moist (2.3 kg dry) soil $_{higher\ Corg}$, 4.0 kg of moist (2.8 kg dry) soil $_{lower\ Corg}$, respectively, was filled into five-litre pots with a height of 16 cm and a diameter of 20 cm. Eight hundred milligrams of fertiliser N (Tab. 1), equivalent to 255 kg N ha^{-1}, were mixed into the upper half of the soil in three replicates. In total, 66 pots were in the greenhouse chamber. Perennial ryegrass seeds (*Lolium perenne*, L. cv. 'Birger'; 1.5 g) were sown at a depth of 0.5 cm two weeks after the addition of the fertiliser. The pots were covered with plastic until the germination of the ryegrass and were regularly watered to achieve a maximum 60% water holding capacity, which corresponded to 4.1 kg and 4.7 kg of soil (soil $_{higher\ Corg}$ / soil $_{lower\ Corg}$), respectively.

The ryegrass was cut to 1.5 cm stubble height 26, 48, 75, 106 and 131 days after sowing. Ryegrass was oven-dried for 24 h at 105 °C to determine the dry matter yield (DM). Samples were milled and their total N content was analysed according to the dry combustion DUMAS method using varioMax CN, Macro Elementar Analyser, Elementar Analysensysteme GmbH, Hanau, Germany to be able to determine N uptake in ryegrass.

The apparent N utilisation with the model plant perennial ryegrass was calculated over time as the additional N uptake of ryegrass compared to the control divided by the added fertiliser N. Residual soil mineral N after the final harvest was not included.

The apparent N utilisation was calculated as:

Apparent N utilisation (%) = (A – B) / C × 100,
A: Cumulative N uptake of fertilised ryegrass shoots at harvest in mg pot^{-1},
B: Cumulative N uptake of unfertilised ryegrass shoots (control) at harvest in mg pot^{-1},
C: N fertilised (= 800 mg pot^{-1}).

Statistical analyses

Statistical analysis was carried out using SAS (SAS 9.2; SAS Institute, Cary, NC). One factor analysis of variance with Tukey/Kramer HSD test at the significance level $\alpha = 0.05$ was applied for the comparison of the means between organic fertilisers. A two factor analysis of variance with Tukey/Kramer HSD was applied to determine how organic fertilisers and soils affect dry matter yield and apparent N utilisation and to determine whether or not there were interaction effects between organic fertilisers and different soils. Regression and correlation analyses were calculated using the SAS procedures "proc reg" and "prog corr".

RESULTS

Dry matter yield

The pot experiment was conducted to determine the availability of organic-fertiliser N to ryegrass. DM yield was influenced both by the fertiliser and by the soil (Fig. 1). A fertiliser application to soil $_{\text{lower Corg}}$ increased DM yield compared to the unfertilised control in all five cuts, but the application of white clover residues resulted in a lower DM yield in the first cut than in the unfertilised treatment (Fig. 1a). In contrast, for white clover residues, the DM yield of the third and fourth cut was very high compared to the other fertiliser treatments. Fishmeal and Pioner complete 6-1-3® had an especially high DM yield during the first three cuts. Compared to these fertilisers, the application of mushroom, cow, sheep and horse compost resulted in lower DM yields during the first two cuts. In contrast, chicken compost and coarse meal of faba beans had only a slightly higher DM yield during the first two cuts than the unfertilised control, but after the second cut their DM yield was higher than those of the other composts. The DM yield of chicken compost at the fourth cut was still high, while all other composts gained just a small DM yield increase after the third cut. Plant compost was characterised by only a slightly higher DM yield during all five cuts than the unfertilised control. After the fourth cut, for all fertiliser treatments only a slight DM yield increase was achieved. After the fifth cut, DM yield was higher with fertilisers with a high N content. The highest DM yields were achieved with fishmeal (29 g pot^{-1}) and Pioner complete 6-1-3® (28 g pot^{-1}), followed by white clover residues (25 g pot^{-1}). Intermediate and not significantly different values of DM yields were obtained for composted animal residues (18-22 g pot^{-1}) and mushroom compost (19 g pot^{-1}). The lowest DM yields were achieved with plant compost (16 g pot^{-1}) and the control (14 g pot^{-1}); however, there were mainly no significant differences to the animal composts and to mushroom compost.

In contrast, soil $_{\text{higher Corg}}$ acted differently (Fig. 1b): a fertiliser application did not increase DM yield at any of the five cuts. Especially white clover residues, but also coarse meal of faba beans had a much lower DM yield than the unfertilised control during all cuts. In contrast to soil $_{\text{lower Corg}}$, the increase in DM yield was nearly comparable in all five cuts. After the last cut, the unfertilised control (36 g pot^{-1}) had a similar yield level to the composted animal fertilisers (31-40 g pot^{-1}), mushroom compost (34 g pot^{-1}) and plant compost (30 g pot^{-1}). However, when fertilisers with a high N content were applied, DM yield was significantly suppressed to 17-23 g pot^{-1} (white clover residues, coarse meal of faba beans, Pioner complete 6-1-3®), whereas DM yield obtained with fishmeal (29 g pot^{-1}) was higher.

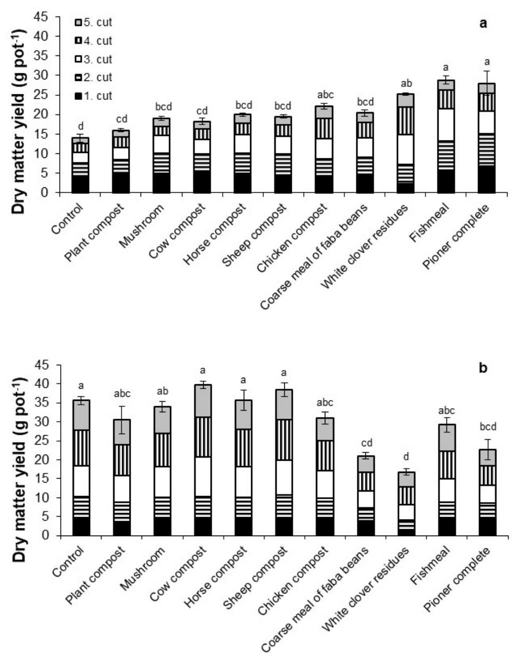

Figure 1. Dry matter yield of ryegrass after application of organic fertilisers to “soil $_{\text{lower Corg}}$” (a) and “soil $_{\text{higher Corg}}$” (b). Ryegrass was grown for 131 d at a maximum 60% water holding capacity and shoots were harvested five times. Differences between fertilisers are based on Tukey’s HSD test and different letters indicate statistically significant differences between means of total dry matter yield at the p = 0.05 level (n=3). Error bars indicate standard deviations of total dry matter yield.

The results of the two-way ANOVA revealed that there was a statistically significant difference in DM yield of ryegrass between both organic fertilisers ($F(10)=3.08$, $p < 0.0048$) and soils ($F(1)=88.95$, $p < 0.0001$) as well as their interaction ($F(10)=9.94$, $p < 0.0001$).

N utilisation

The time course of the apparent N utilisation in ryegrass differed strongly depending on the organic fertiliser used and showed a different pattern among soils (Fig. 2). For soil $_{\text{lower Corg}}$ (Fig. 2a), most of the N – in relation to the total mineralised N at the end of the experiment – was already released before the second cut (about 50% of the total N uptake) except for white clover residues, chicken compost and coarse meal of faba beans. Thereafter, the increase in the apparent N utilisation was markedly lower, but very high for white clover residues. During the whole experiment Pioner complete 6-1-3® had the highest N uptake of all the fertilisers (85%). The cumulative fertiliser N uptake of ryegrass was also high for fishmeal (75%) and white clover residues (80%). However, at the beginning of the experiment, fertiliser N was immobilised in the clover treatment, but after that apparent N utilisation increased rapidly. A medium apparent N utilisation in ryegrass (40-50%) was achieved for chicken compost and coarse meal of faba beans, but seems not to have been fully completed at the end of the experiment. The cumulative fertiliser N uptake was lowest (10-20%) for plant, sheep, cow and horse compost as well as for the reference fertiliser mushroom compost.

In contrast, soil $_{\text{higher Corg}}$ (Fig. 2b) was characterised by an immobilisation of N with nearly all fertilisers. The immobilisation even increased with longer ryegrass growing period and was highest for fertilisers with a high N content. At the end of the growth period, N immobilisation amounted to 60-70% for Pioner complete 6-1-3® and coarse meal of faba beans. Plant compost, white clover residues, fishmeal, chicken compost and mushroom compost had an N immobilisation of 10-30%, while horse compost immobilised only slightly.

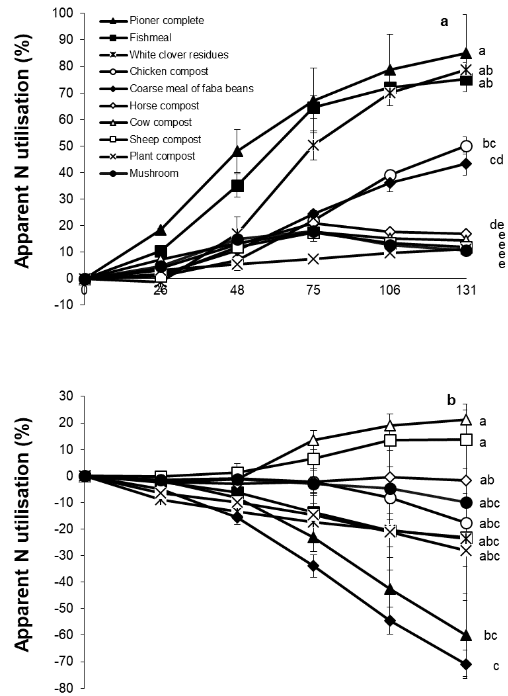

Figure 2. Apparent N utilisation of organic fertilisers by perennial ryegrass during the pot experiment with "soil $_{\text{lower Corg}}$" (a) and "soil $_{\text{higher Corg}}$" (b). Ryegrass was grown for 131 days at a maximum 60% water holding capacity, and shoots were harvested five times. Differences between fertilisers are based on Tukey's HSD test and different letters indicate statistically significant differences between means at the $p = 0.05$ level (n=3). Error bars indicate standard deviations and are contained within the symbol if not indicated.

All of these fertilisers immobilised N during the whole growth period. In contrast, an application of sheep and cow compost to ryegrass was characterised at the beginning of the growth period by an N immobilisation, but after about 10 weeks of growth the immobilised N in these treatments mineralised and N utilisation amounted to 15-20% at the end of the growth period. Interestingly, this amount was comparable to the apparent N utilisation of the same fertilisers at soil $_{\text{lower Corg}}$.

The results of the two-way ANOVA revealed that there was a statistically significant difference in apparent N utilisation by ryegrass in all five cuts by both organic fertilisers (last cut: F(9)=3.65, p = 0.0021) and soils (last cut: F(1)=173.45, p < 0.0001) as well as their interaction (last cut: F(9)=13.78, p < 0.0001).

Relationship of N utilisation and fertiliser characteristics

As a general rule, it can be said that fertilisers with a higher N content showed a higher apparent N utilisation in ryegrass in soil $_{\text{lower Corg}}$ and a higher negative apparent N utilisation in ryegrass in soil $_{\text{higher Corg}}$. However, this relationship was very weak (Fig. 3a: r^2=0.50 *; Fig. 3b: r^2=0.12 $^{\text{n.s.}}$) and not fitting for all fertilisers (e.g. fishmeal).

The C:N ratio explained the relationship slightly better than N content, even though the relationship was still weak (Fig. 4a: r^2=0.61 **; Fig 4b: r^2=0.30 $^{\text{n.s.}}$). Generally it can be said that in soil $_{\text{lower Corg}}$, fertilisers with a high C:N ratio (e.g. composted animal manure) showed a low apparent N utilisation, whereas fertilisers with a low C:N ratio (e.g. fishmeal, Pioner complete 6-1-3®) are rapidly available for plants and resulted in a high apparent N utilisation. However, some exceptions can also be found here. For instance, white clover residues had a medium C:N ratio, but the apparent N utilisation was high. In contrast, in soil $_{\text{higher Corg}}$, fertilisers with a high C:N ratio (most of the composted animal manures) showed a higher N utilisation than fertilisers with a low C:N ratio (e.g. Pioner complete 6-1-3®).

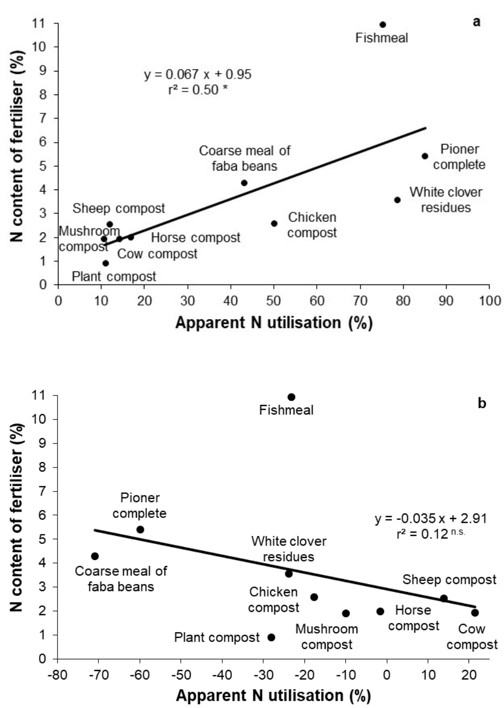

Figure 3. Relationship between apparent N utilisation of applied total N in perennial ryegrass and N content of organic fertilisers with "soil $_{\text{lower Corg}}$" (a) and "soil $_{\text{higher Corg}}$" (b). Apparent N utilisation was calculated based on the cumulative N uptake (five cuts) during 131 days of growth.

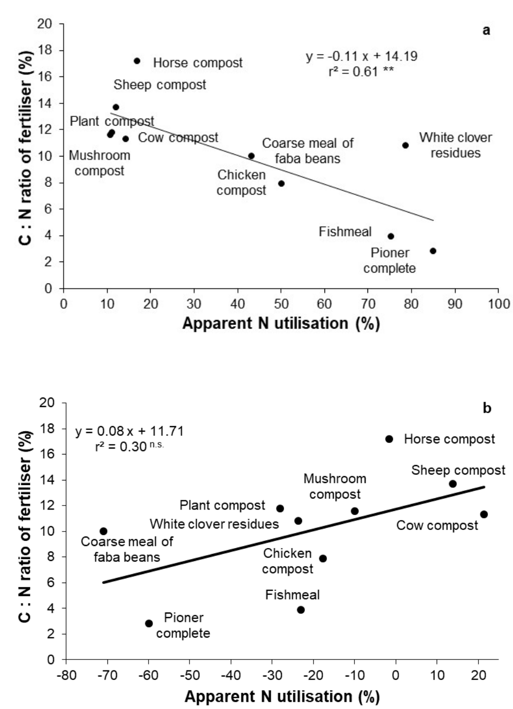

Figure 4. Relationship between apparent N utilisation of applied total N in perennial ryegrass and C:N ratio of organic fertilisers with "soil $_{\text{lower Corg}}$" (a) and "soil $_{\text{higher Corg}}$" (b). Apparent N utilisation was calculated based on the cumulative N uptake (five cuts) during 131 days of growth.

DISCUSSION

The tested organic fertilisers differed strongly regarding to DM yield and apparent N utilisation in ryegrass. N release was described by the N content and the C:N ratio of the tested fertilisers, though with a low correlation, suggesting that factors other than the N content and the C:N ratio must be responsible for a low, medium or high apparent N utilisation. Fertilisers that are characterised by a low N content, and thus a relatively high C:N ratio, resulted in a low and slow apparent N utilisation in soil $_{\text{lower Corg}}$, while this fertiliser group resulted in soil $_{\text{higher Corg}}$ in a slow but either low or slightly negative apparent N utilisation. In contrast, most of the fertilisers that featured a high N content, and thus revealed a low C:N ratio, provided a high amount of plant available N in soil $_{\text{lower Corg}}$. Consequently, the dynamics in DM yield during the different cuts reflect a fast N release. Therefore, the high apparent N utilisation rates can be explained by the high proportion of readily available N_{org} for microbial conversion in the soil (Stadler 2006). Furthermore, the results emphasised that the type and processing of organic N fertilisers was largely responsible for the N composition and mineralisation properties as was also observed by Stadler et al. (2006). For instance, the poorer performance of the N content with respect to C:N ratio in predicting the N release from fertilisers could be ascribed to the relatively high N content of fishmeal. However, a close relationship between the above mentioned fertiliser characteristics and their N mineralisation was found by Stadler et al. (2006) and Sradnick & Feller (2020). Therefore, fertiliser N content and C:N ratio are suitable indicators for predicting the N release from organic fertilisers, provided the fertiliser characteristics are sufficiently different (Stadler et al. 2006). Often a critical C:N ratio for net N immobilisation of 20-30 was reported (Trinsoutrot et al. 2000, Chen et al. 2014), while lower critical C:N ratios are also known. For example, Geisseler et al. (2021) mentioned a threshold of about 15 in their review. In contrast, in the present experiment, N immobilisation occurred in the more fertile soil already with a C:N ratio of much less than 10. Therefore, it can be assumed that, in addition to the C:N ratio of fertilisers, other factors might be attributed to N mineralisation / immobilisation processes of organic fertilisers. Potential interactions between organic fertilisers and soils can be expected. DM yield and apparent N utilisation in ryegrass was not only influenced by the fertiliser, but also by the soil and the interaction of fertiliser and soil. While application of organic fertilisers to soil $_{\text{lower Corg}}$ promoted plant growth and is characterised by an N mineralisation of all fertilisers, in soil $_{\text{higher Corg}}$ an immobilisation of N with nearly all fertilisers occurred. The immobilisation was even more pronounced for organic fertilisers with a high N content and consequently low C:N ratio and increased with a longer growing period possibly due to the inhibition of growth due to an excess supply of N. This is confirmed by the fact that cow and sheep compost were the only fertilisers which did not suppress growth (DM yield) and released N very slowly. Indeed, Ren et al. (2014) also stated that soils with higher C_{org} contents may immobilise more N. However, in the literature no obvious relation of soil organic matter to N mineralisation is reported (Bending et al. 2002, Stadler et al. 2006). Soil characteristics influenced N mineralisation more strongly for fertilisers with a lower N content (Stadler et. al. 2006). In contrast, the presented results showed that fertilisers with a high N content (e.g. fishmeal) caused a higher variation in N mineralisation depending on the C_{org} content of the soil (high N mineralisation in soil $_{\text{lower Corg}}$, N immobilisation in soil $_{\text{higher Corg}}$), whereas this variation was less pronounced for fertilisers with a lower N content (composted animal manures) because of less available N.

Due to the regular application of mushroom compost to soil $_{\text{higher Corg}}$, the total organic matter and mineralisable N of the soil increased. Therefore, it can be expected that the turnover of the organic substance might affect the N utilisation of organic fertilisers. Indeed, Thomsen et al. (2003) observed that the N turnover of organic matter added to soil in crop residues and manure affects the availability of N mineralised from both added and native soil organic matter. It is possible that too much N was applied to soil $_{\text{higher Corg}}$, e.g. in the form of fishmeal and Pioner complete 6-1-3®, due to the high availability of N from fertiliser applications in the form of mushroom compost from previous years and therefore, this soil was not able to deal with all the available N. Consequently, the newly applied fertiliser N was immobilised instead. Soil samples of mineral N could have given additional information. However, the N content in ryegrass, which was still high for all fertilisers in the fourth and fifth cut (around 4.5% N, data not shown) in soil $_{\text{higher Corg}}$ is emphasising a high N supply, while in soil $_{\text{lower Corg}}$, N content was dependent on the fertiliser treatment (4-4.5% for chicken compost, coarse meal of faba beans, Pioner complete 6-1-3® and plant compost; 1.5-2.5% for mushroom compost, sheep compost, unfertilised control and cow compost). Stadler (2006) observed that the lower apparent N utilisation of peas (3.7% N) was more pronounced in the higher C_{org} content soils. Moreover, Thönnissen et al. (2000) reported an often marginal effect of green manure on yield of tomatoes in fertile soils (high soil organic matter), but its high effect on poor soils (low soil organic matter). Magdoff (1991) obtained the highest amount of available N from soils with medium N_t and C_{org} content. He explained this result by the fact that at low organic matter contents, the mineralisation rate was high, but less N was available due to the low content of organic N. Soils high in N_t and C_{org} had low mineralisation rates which consequently resulted in low amounts of mineralised N as well. This might explain the high N mineralisation of the unfertilised control observed in soil $_{\text{higher Corg}}$. However, as soil mineral N content has not been measured before fertiliser application, no clear interpretation of this issue can be made. Magdoff (1978) concluded that soils with a high mineralisation rate of soil organic matter may also rapidly mineralise N from manure, whereas in a soil with a low soil N mineralisation rate, manure N release will be lower. However, this was not in line with the presented results.

Commercial organic fertilisers of animal origin (fishmeal) with a fast and high N release rate, as well as commercial industrially processed plant residues (Pioner complete 6-1-3®) should be highlighted as efficient organic fertilisers on the less fertile soil. Indeed, Sradnick & Feller (2020) also reported that due to their high release rate of inorganic N, the use of commercial organic fertilisers of animal origin meets the demand of plant species with high N requirements in vegetable production systems. Since their N to P ratio is relatively high, they qualify as a suitable fertilisation option in intensive organic production systems. The presented results further indicate that a higher efficiency of fertiliser could be reached by applying the aforementioned fertiliser group in more than one application for long-growing crops to better match the N release from fertilisers and the N demand of long growing crops.

Since only small amounts of organic N are available for N uptake from composted organic material (manure, plant residues) – except chicken compost – into the plant in the first four months of application, these organic fertilisers are only suitable for soil fertility improvement. Thus these soil amendments represent a fertiliser with long-term N mineralisation. As the total N utilisation of mushroom compost was comparable to the other composted animal manures, these fertilisers can act as a replacement for mushroom compost. However, despite the absence of livestock at most Icelandic vegetable producers, animal manure could be used from farms with organic animal production or from farms with conventional production after composting.

CONCLUSIONS

In the year of application, organic fertilisers were able to mineralise 10% (compost) to 80% (fishmeal, Pioner complete 6-1-3®) of the total N applied on the less fertile soil. Consequently, it can be assumed that the regular application of fertilisers with a low N mineralisation over several years will tend to increase the total soil organic matter and N that can potentially be mineralised. It should therefore be kept in mind whether long-term application of these fertilisers may require a modified application strategy. In addition, application strategies need to be adjusted depending on the selected greenhouse soil as, for the more fertile soil most fertilisers decreased the DM yield and consequently N was immobilised. Cow and sheep compost with a slow N release turned out to be the best suitable fertilisers on these soils. More research is needed to characterise soils that result after the application of organic fertiliser in N immobilisation processes. Fertiliser strategies need to be adapted to decrease and overcome high levels of N immobilisation and to maintain the recommended nutrient levels for optimal plant growth dependent on their soil fertility. However, for all greenhouse soils, the mineralisation / immobilisation properties of organic fertilisers can be predicted through the N content of the fertilisers and their C:N ratio, even though the precision of this relationship is influenced by the soil. Crucially, the prohibition of mushroom compost should not affect organic vegetable growers as there are at least equal (composted animal manures) fertilisers available.

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