Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land

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Summary—Zusammenfassung

Knowledge on short-term and long-term availability of nitrogen (N) after application of organic fertilizers (*e.g.*, farmyard manure, slurry, sewage sludge, composts) provides an important basis to optimize fertilizer use with benefits for the farmer and the environment. Nitrogen from many organic fertilizers often shows little effect on crop growth in the year of application, because of the slow-release characteristics of organically bound N. Furthermore, N immobilization after application can occur, leading to an enrichment of the soil N pool. However, this process finally increases the long-term efficiency of organic fertilizers. Short-term N release from organic fertilizers, measured as mineral-fertilizer equivalents (MFE), varies greatly from 0% (some composts) to nearly 100% (urine). The most important indicators to be used for predicting the short-term availability of N are total and NH_4^+-N contents, C : N ratio (especially of the decomposable organic fraction), and stability of the organic substances. Processing steps before organic fertilizers are applied in the field particularly can influence N availability. Composting reduces mineral-N content and increases the stability of the organic matter, whereas anaerobic fermentation increases NH_4^+-N content as well as the stability of organic matter, but decreases the C : N ratio remarkably, resulting in a product with a high content of directly available N. Nevertheless, long-term effects of organic fertilizers rather slowly releasing N have to be considered to enable optimization of fertilizer use. After long-term application of organic fertilizers, the overall N-use efficiency is adequate to a MFE in the range of 40%–70%.

Key words: biogenic waste / nitrogen availability / nitrogen-use efficiency / organic fertilizer

Kurz- und langfristige Stickstoffwirkung organischer Dünger nach langjähriger Anwendung im Ackerbau

Kenntnisse über die kurz- und langfristige Stickstoff (N)-wirkung organischer Dünger (z. B. Stallmist, Gülle, Klärschlamm, Kompost) sind Voraussetzung für die Optimierung der Anwendung im Ackerbau bezüglich Stickstoffeffizienz und Umweltverträglichkeit. Organische Dünger zeigen häufig unmittelbar nach der Anwendung eine schwache Wirkung als Folge der Immobilisation des mineralischen sowie der langsamen Mineralisation des organisch gebundenen Stickstoffs. Die Pflanze nimmt dann den Stickstoff überwiegend aus dem N-Pool des Bodens auf, der durch die Anwendung organischer Dünger über mehrere Jahre angereichert wurde. Die kurzfristige N-Wirkung organischer Dünger lässt sich auf Basis von Mineraldünger-Äquivalenten (MFE) vergleichen. Sie schwankt von 0% (Frischkompost) bis nahezu 100% (Jauche). Die wichtigsten Kenngrößen für die Abschätzung der kurzfristigen Stickstoffwirkung sind die Gehalte an Gesamt- und NH_4^+-N, der C:N-Quotient (insbesondere jener der organischen Substanz) sowie die Abbaustabilität der organischen Substanz. Die Stickstoffverfügbarkeit wird durch die Art der Aufbereitung des organischen Düngers beeinflusst. Kompostierung mindert den Gehalt an mineralischem Stickstoff und erhöht die Stabilität der organischen Substanz. Anaerobe Fermentation liefert organische Dünger mit stabiler organischer Substanz, hohen Gehalten an NH_4^+-N und niedrigen C:N-Quotienten. Der in diesen Fermentationsrückständen enthaltene Stickstoff wird deshalb von den Pflanzen gut und schnell verwertet. Für eine Optimierung der Düngung bei langsam bis mittelschnell wirkenden Düngern muss deren Langzeitwirkung berücksichtigt werden. In Abhängigkeit von der Sofortwirkung erreichen diese Dünger nach längerer Anwendung eine N-Verwertung entsprechend einem MFE von 40–70 %.

1 Introduction

Basic principles to ensure a high utilization of N from mineral fertilizers for agricultural production are well established and processes that influence N availability are understood. Knowledge on crop-specific fertilizer requirements and appropriate timing and application strategies enable farmers to maximize crop yield and to reduce risks for N losses (*Gutser* and *Ebertseder*, 2002a). However, increasing the N-use efficiency of organic fertilizers remains an important issue for research activities.

Soils and plants "recall" the history of previous organic-fertilizer application longer than that from mineral fertilizers. This is reflected in the short- (N effects in the year of application) and long-term (effects of previously applied N) N supply for the crop. Nitrogen transformation in soils that received organic fertilizers in the past is a complex phenomenon. *Dittert* et al. (1998) reviewed the turnover of liquid and solid manures in soils with emphasis on N availability for plant growth, N-transformation processes (*i.e.*, mineralization, immobilization, nitrification, and denitrification), and the emission of trace gases. Our work is mainly focused on the quantification of N use from organic fertilizers by plants in the year of application as well as in subsequent years. The aim is to enable predictions of the N availability of traditional organic fertilizers (*e.g.*, farm manure, slurry) and those, which have

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been recently introduced for agricultural use (*e.g.*, composts, residues from biogas plants). The main objective is to describe how the conversion of organically bound N in this kind of fertilizers into readily available N for plant growth can be quantified. Recommendations for an appropriate product-specific use of organic fertilizers are also presented.

2 Experimental set-ups

The efficiency of N derived from organic fertilizers was examined in aerobic incubation experiments with a variety of soils (for details see below) and various fertilizers. Several field experiments, designed to collect data on yield and net mineralization rates, were carried out for one or more years (*Messner* and *Amberger*, 1987; *Dosch* and *Gutser*, 1996b). The experiments included various agricultural crops (*e.g.*, winter wheat, winter barley, maize, sugar beet). Crops received identical amounts of total N *via* organic fertilizers with or without additional mineral N. Results from long-term fertilizer experiments, including one lysimeter experiment, running over a period of 15 y, were also taken into account (*Gutser* and *Dosch*, 1996). Organic fertilizers used for these experiments were obtained from well-managed farms. Attention was given to ensure representative sampling and to avoid N losses (especially in the form of NH_3) during processing and storage.

The experimental site in Freising (40 km north of Munich, Germany) is characterized by a semi-humid climate with an annual precipitation of around 800 mm and an average air temperature of 7.8°C. The soil can be classified as a silty loam with 15%–20% clay and 55%–70% silt. Topsoil was used for the incubation experiments. The experimental soils were previously supplied with mineral fertilizers and received occasionally organic-manure amendments. Average C_{org} and N_t contents of the topsoil ranged between 1.0%–1.4% C and 0.12%–0.15% N, respectively.

The N availability from organic fertilizers was related to the availability of mineral-fertilizer N by calculating the apparent mineral-fertilizer-N equivalents (MFE):

$$MFE\ [\%] = N_{of} \times 100\% / N_{mf}$$

with N_{of} being the crop N uptake in the treatment with organic-fertilizer application and N_{mf} N uptake in the treatment with mineral-N application, both corrected for the N uptake from a control treatment (no N application to quantify N uptake from soil N mineralization).

MFE can be calculated on a short-term or long-term basis as described later on. If N content in the plant biomass at harvest was not measured, MFE was determined based on the yield and average values on N content for the different crops. MFE gives an indication of the utilization of organic fertilizers compared with mineral-fertilizer N and enables comparisons of the N availability for different organic fertilizers in different years and on different soils (*Thomsen*, 2004). For example, the application of 100 kg N *via* an organic fertilizer with an MFE value of 30% will result in the same crop N uptake as that of 30 kg of mineral-fertilizer N. To quantitatively estimate available N from organic fertilizers, N-uptake efficiency from mineral fertilizer was assumed to be 60% in the short-term and to increase to 85% after long-term application.

3 Availability of mineral- and organic-fertilizer N in soil and uptake by plants

Mineral and organic fertilizers differ markedly with regard to their transformation in soils and utilization of the applied nutrients by plants (Fig. 1). During the year of application, plants take up the majority of the applied mineral-fertilizer N (50%–80%; on average 60%). Associated changes in the soil N pools are usually small. The level of optimal N fertilization can be determined based on the removal of N in the harvested crop, allowing for an extra N need of 10%–20% to account for some unavoidable N losses.

By contrast, N derived from organic fertilizers acts mainly *via* the soil N pool. The direct utilization in the year of application is relatively small, because of the slow-release characteristics of organically bound N and the medium- and long-term N immobilization in soils (*Tyson* and *Cabrera*, 1993; *Whitmore*

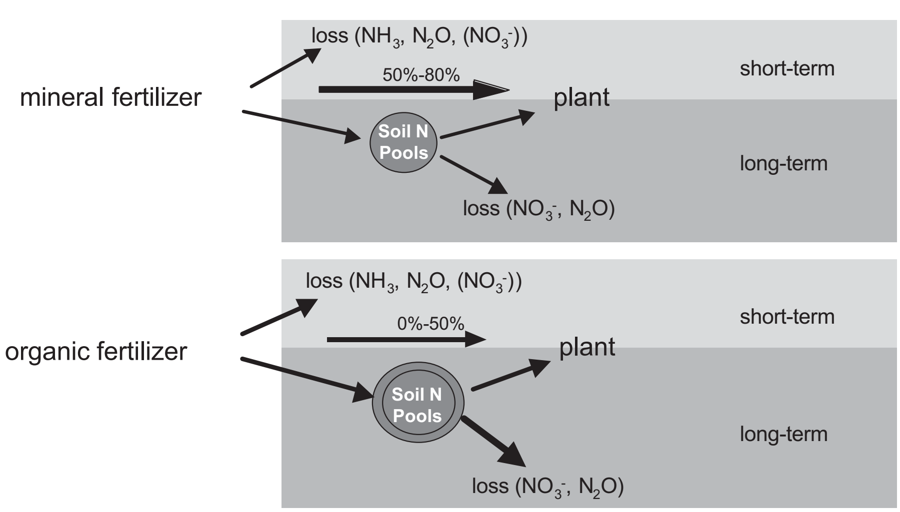


Figure 1: Schematic overview on short- and long-term effects of mineral and organic fertilizers on soil N availability.
Abbildung 1: Schematische Darstellung der kurz- und langfristigen Effekte mineralischer und organischer Dünger auf die N-Verfügbarkeit im Boden.

and *Schröder*, 1996; *Jensen* et al., 2000; *Sørensen* and *Amato*, 2002). Re-mineralized N from soil N pools will be used by plants, however, this N inevitably represents a potential source of N losses. Therefore, assuming NH_4^+-N-conserving application techniques are adopted, the N supply with organic fertilizers has to be calculated with a 30%–40% surcharge based on the N removed by plants even in a system that has been optimized in the past. It has to be kept in mind that both the soil N pool and the yield stability increase with higher organic-fertilizer application rates, but so do the risks for higher N losses (*Loro* et al., 1997; *Kilian* et al., 1998; *Körschens* et al., 1998; *Sommer* and *Hutchings*, 2001; *Khalil* et al., 2002). In many countries, the maximum amounts of N supplied *via* organic fertilizers are therefore regulated (*e.g.*, *Anonymous*, 1996).

A special situation can be seen in organic-farming systems. Although depending solely on organic fertilizers, soil N accumulation and thus risks for N losses are low, because the amount of organic fertilizers available on the farm is limited, due to lower livestock density and restricted purchase of animal fodder. However, frequently this results in lower crop yields compared to conventional farming. In general, it seems that high crop yields cannot be achieved without high N losses when organic fertilizers represent the main source of nutrients. A combination of organic and mineral fertilizers could be a more appropriate approach, because in contrast to the uncertain effects of organic fertilizers, mineral-N application enables planning the supply of nutrients to the plant as and when necessary.

The N balance over several years is considered to be an important indicator for the assessment of N use and the risk for environmental pollution. Especially on intensively managed livestock farms, the long-term effects of organic-fertilizer application were often not taken into account. In Germany, the annual N surplus (*i.e.*, N supply *via* fertilizer application minus N removal with the harvested crops) increased dramatically up to 150 kg N ha^{-1} y^{-1} as an average for agricultural land at the end of the 1908s. During the last ten years, economic constraints as well as the imposition of fertilization regulation and advice halted this trend, resulting in a considerably reduced N surplus nowadays (*Bach* and Frede, 1998). Figure 2 quantifies the N accumulation and availability in soils over time and also shows annual N utilization (immediate and residual effects) of two fertilizers with different MFE. Figure 2 is derived from lysimeter and field experiments as well as from theoretical calculations (*Gutser* and *Claassen*, 1994).

Fertilizer A, which has a slow-release characteristic, resulted in a larger soil N accumulation than fertilizer B. A quasi-steady state can be reached after 30 or more years (*Gutser* and *Claassen*, 1994; *Chang* and *Janzen*, 1996; *Hülsbergen* et al., 1996; *Yang* and *Janssen*, 1997). Even after long-term application, fertilizer A does not reach the N-use efficiency of fertilizer B, which can be seen by the lower N uptake by plants for fertilizer A. This can be explained by the higher N losses from soil. Overall, the N-turnover rates in soils with fresh or older fertilizer residues can be seen to be important factors in determining N release (*Gutser* and *Dosch*, 1996; *Sørensen* and *Amato*, 2002; *Hao* et al., 2003).

4 Assessment of N availability from organic fertilizers

The availability of N from organic fertilizers is considerably influenced by site (*e.g.*, soil, climate), soil fertility (*e.g.*, turnover rate), crop type (length of the growing period during the warmer season), and fertilizer-application rates over years (*Whitmore* and *Groot*, 1997; *Hadas* et al., 2002). Depending on the duration of experiments, MFE values of organic fertilizers can be specified for the short-term N release (effect in the year of application) or the long-term N release (short-term release and cumulative effect of regular applications in previous years).

Organic fertilizers with low contents of NH_4^+-N and relatively high C : N ratios (*e.g.*, manure, composts), which release nutrients slowly, show a strongly increased N utilization by crops over time due to the mineralization of accumulated N in soils (Fig. 3).

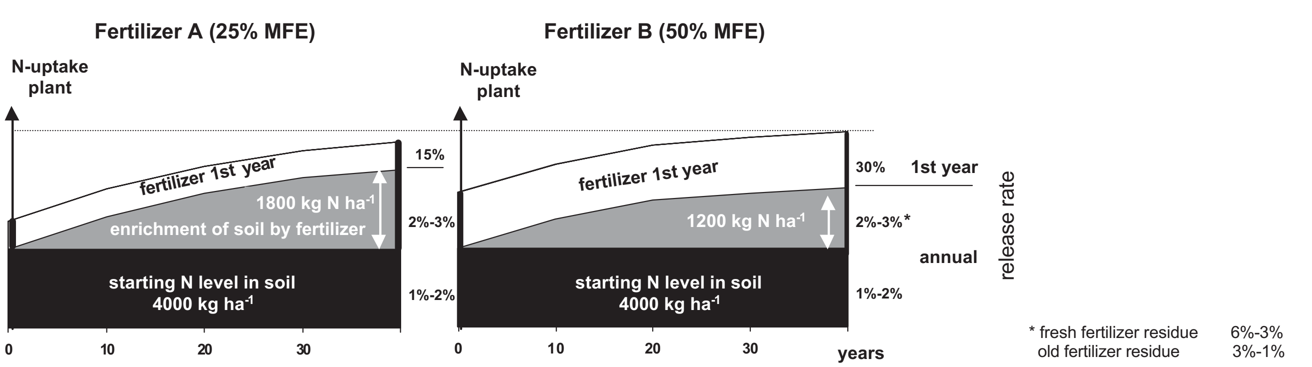


Figure 2: Comparison of the long-term effect of regularly applied organic fertilizers with different N availability according to their mineral-fertilizer equivalents (MFE) in the year of application: fertilizer A with 25% MFE *versus* fertilizer B with 50% MFE (application rate of both fertilizers were 100–140 kg total N ha^{-1} y^{-1}).

Abbildung 2: Vergleich der Langzeitwirkung verschiedener organischer Dünger mit unterschiedlicher N-Verfügbarkeit beurteilt anhand der Mineraldüngeräquivalente (MFE) im Anwendungsjahr: Dünger A mit 25% MFE bzw. Dünger B mit 50% MFE (Düngungsniveau: 100–140 kg Gesamt-N ha^{-1} a^{-1}).

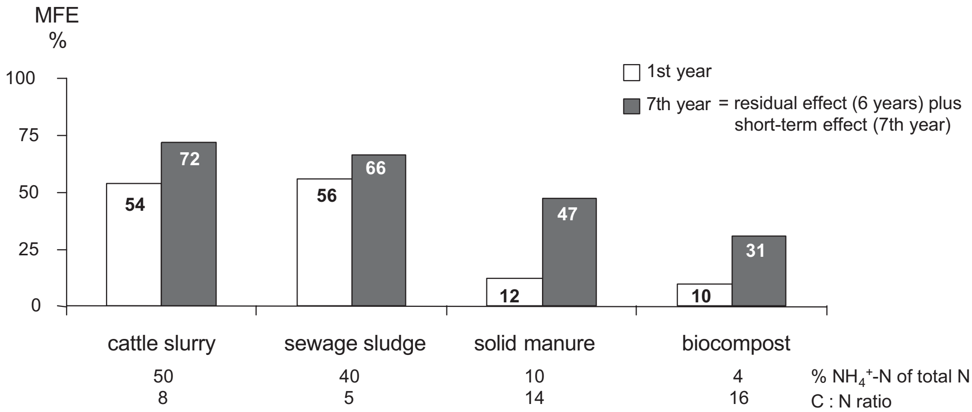
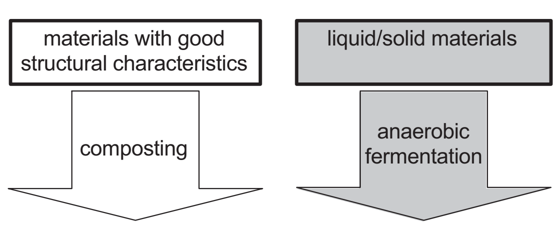


Figure 3: Short- and long-term effects of organic fertilizers expressed as mineral-fertilizer equivalents (% MFE), based on nitrogen removed by plants in a pot experiment (annual application rate 750 mg total N pot^{-1}).
Abbildung 3: Kurz- und langfristige Wirkung organischer Dünger dargestellt als Mineraldüngeräquivalente (% MFE), basierend auf den N-Entzügen der Pflanzen im Gefäßversuch (jährliche Applikationsmenge 750 mg Gesamt-N Gefäß$^{-1}$).

5 Factors influencing the short-term N availability of organic fertilizers

The short-term N availability of organic materials depends largely on two factors: (1) mineral-nitrogen content and (2) N content of organic substances. High mineral-nitrogen contents usually lead to good short-term N availability (*Furrer* and *Bolliger*, 1978; *Serna* and *Pomares*, 1993; *Dosch* and *Gutser*, 1996b). Organic fertilizers based on plant biomass derived after fermentation or hydrolysis as well as animal excreta (urine in particular) typically contain high amounts of NH_4^+-N (*Messner* and *Amberger*, 1987; Kape et al., personal comunication). However, the availability of N also depends on the amount of carbonaceous materials present in these substances. When organic fertilizers consist of low-N organic substances (C : N ratio > 15), N availability can be limited due to immobilization in soil (*i.e.*, use of mineral N to build microorganism protein). This process is normal for manure, which is rich in straw as well as for fresh compost (*Kirchmann*, 1985; *Gutser* and *Dosch*, 1996). Organic fertilizers with high-N organic substances normally show a high N release in the year of application, *e.g.*, leftovers from slaughterhouses like horn and meat meals (C : N ratio = 3–4), plant residues like coarse meal of legumes (N content > 5%), or sewage sludge (C : N ratio = 3–5) (*Warren* et al., 1958; *Furrer* and *Bolliger*, 1978; *Smith* and *Hadley*, 1988). Short-term N availability from organic fertilizers can be estimated mainly based on these two factors. Predictive models have been developed that use data from infrared-spectroscopy measurements, but they have not yet been used in practice (*Das* et al., 1993; *Serna* and *Pomares*, 1993; *Hue* and *Liu*, 1995; *Palm* and *Rowland*, 1997; *Capriel* et al., 1999; *Malley* et al., 2002; *Shepard* et al., 2003).

The C : N ratio of an organic substance (and especially its degradable fraction) is the decisive factor for N release from organic matter. However, the estimation of the degradable substance can be difficult (*Palm* and *Rowland*, 1997). As such, the C : N ratio of organic substances can be calculated roughly from their C content and their organically bound nitrogen (N_{org}), which represents the difference between total and mineral N. When the C : N_{org} ratio is below 6–7, a high N release can be expected. Dilution of liquid manure or grinding of solid organic fertilizers can increase the availability of N, and thus N uptake by the crop. Changes upon processing have to be considered as well (Fig. 4). While composting results in a product that can be characterized by low contents of NH_4^+-N along with stable organic substances, anaerobic fermentation will lead to a product with high content of mineral N. For these reasons, short-term availability of



organic substance	amount	decrease	decrease
	stability	increase	increase
	humus reproducibility	increase	increase
C : N ratio		decrease	decrease
NH_4^+-N		decrease	sharp increase
pH value		increase	sharp increase

Figure 4: Impact of composting and anaerobic fermentation (biogas technology) on indicators used to describe N availability from organic fertilizers.
Abbildung 4: Einfluss von Kompostierung und anaerober Fermentation (Biogas-Technologie) auf Indikatoren, welche die N-Verfügbarkeit von organischen Düngern anzeigen.

organic N from mature compost is low (*Eghball* and *Power*, 1999; *Van Kessel* et al., 1999; *Sommer*, 2001; *Huang* et al., 2003). A characterization of the stability of organic matter, although difficult, can be deduced from its chemical composition (*e.g.*, content of lignin, phenolics, soluble carbon) or it can be determined using certain biological methods (*Palm* and *Rowland*, 1997; *Henriksen* and *Breland*, 1999).

Residues of biogas plants are generally rich in NH_4^+-N. Moreover, the mineral N is hardly immobilized in soil because the remaining organic substance is highly stable (*i.e.*, it does not promote immobilization of N), resulting in a high N availability (*Freytag* and *Ransch*, 1982; *Messner* and *Amberger*, 1987; *Gutser* and *Dosch*, 1996). This fertilizer is also characterized by its fast infiltration into the soil and rather small NH_3 losses, even when applied to the soil surface. However, direct incorporation of the liquid organic fertilizers into the soil should be preferred (*Sommer*, 2001; *Thomsen*, 2001; *Preusch* et al., 2002; *Wulf* et al., 2002a, b; *Chantigny* et al., 2004). The use of separation techniques further improves the availability of the N retained in the liquid fractions (*Dosch* and *Gutser*, 1996a, b).

6 Nitrogen availability from selected organic fertilizers

N availability from organic fertilizers can be classified according to their MFE (Fig. 5, Tab. 1). The application of 100 kg N as organic fertilizer saves the use of anywhere between 0–100 kg of mineral-fertilizer N in the year of application. The residual effect of previous fertilizer application is especially important when MFE is less than 70%. This residual effect increases with decreasing short-term N release as well as with the frequency and amount of fertilizer application. When organic fertilizers have been applied over several years, the annually effective percentage of the fertilizer (= sum of the direct and residual effects) can be estimated as follows:

MFE (short-term,%)	MFE (long-term,%)
<20	40–50
>20–40	>50–60
>40–60	>60–70

(see Fig. 5 or Tab. 1)

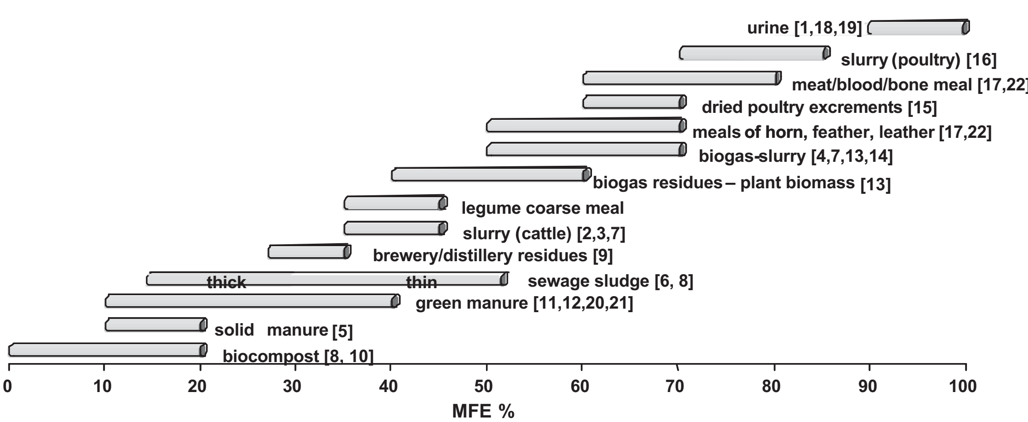
These values represent a useful orientation point for planning fertilizer management. A multi-year N balance (= input by fertilizer minus output by removal) should also be included in the fertilizer planning as a decision-support tool and self-control mechanism.

7 Recommendations for the application of organic fertilizers

General rules for the application of organic fertilizers have to be seen in the context of the short-term N availability. For fertilizers with high NH_4^+ contents (more than 25% of total N), special application techniques have to be used to reduce volatile NH_3 losses. The application of fertilizers with high short-term N availability (MFE > 30%) has to be avoided during the winter season. This is also relevant for solid organic fertilizers, although N release from these products is slower than that of liquid organic fertilizers, which are generally characterized by higher NH_4^+ contents.

The amount of organic fertilizer to be applied has to be adapted to the crop-specific N demand, especially for fertilizers with a MFE higher than 30%. Applications of adequate amounts of organic fertilizers on a year-to-year basis are preferable against application of huge amounts once per crop rotation.

The currently permissible annual maximum load of 170 kg N ha^{-1} y^{-1} (EU nitrate directive 1991) does only refer to solid or liquid farm manure. However, maximum N loads should also include organic fertilizers from other sources (*e.g.*, composts,



[1] *Amberger* et al., 1982a; [2] *Amberger* et al., 1982b; [3] *Dittert* et al., 1998; [4] *Dosch* and *Gutser*, 1996a; [5] *Dosch* and *Gutser*, 1996b; [6] *Furrer* and *Bolliger*, 1978; [7] *Gutser* et al., 1987; [8] *Gutser*, 1996; [9] *Gutser*, 1998; [10] *Gutser* and *Ebertseder*, 2002b; [11] *Gutser* and *Vilsmeier*, 1987; [12] *Honeycutt*, 1999; [13] Kape et al., 2004, personal communication; [14] *Messner* and *Amberger*, 1987; [15] *Nicholson* et al., 1996; [16] *Preusch* et al., 2002; [17] *Smith* and *Hadley*, 1988; [18] *Sørensen* and *Jensen*, 1996; [19] *Thomsen* et al., 1997; [20] *Thorup-Kristensen*, 1994; [21] *Vilsmeier* and *Gutser*, 1987; [22] *Warren* et al., 1958.

Figure 5: Mineral-fertilizer equivalents (% MFE) for several organic fertilizers characterizing N availability in the year of application.
Abbildung 5: Mineraldünger-Äquivalente (% MFE) für verschiedene organische Dünger zur Charakterisierung der N-Verfügbarkeit im Jahr der Anwendung.

Table 1: Typical values for total N content, NH_4^+-N share on total N, and C : N ratio as well as a characterization of the biodegradability of the organic material and mineral-fertilizer equivalents (MFE%) for several organic fertilizers.
Tabelle 1: Typische Gehalte an Gesamt-N, Anteile des NH_4^+-N am Gesamt-N und C : N-Verhältnisse sowie Charakterisierung der Umsetzbarkeit der organischen Materialien und Mineraldünger-Äquivalente (MFE%) für verschiedene organische Dünger.

Fertilizer	N content		Dry matter	NH_4^+-N in total N	C : N ratio	Biodegradability of organic matter	Short-term effect MFE*
			[%]	[%]			[%]
Legume coarse meal	40–60	kg t^{-1}	95	0–5	10–13	high	35–45
Horn/feather/leather meal	130	kg t^{-1}	95	0–5	3–4	high	50–70
Brewery/distillery residues	3	kg m^{-3}	6	0–5	8–10	high	30–35
Meat/blood/bone meal	75–120	kg t^{-1}	95	5–10	3–5	very high	60–80
Green manure	10–35	kg t^{-1}	100	0–10 (NO_3^--N)	10–30	low–medium	10–40
Biocompost	6	kg m^{-3}	60	0–15	13–20	low	0–20
Solid manure	6	kg t^{-1}	25	5–20	12–15	low	10–20
Sewage sludge (high DM)	4–5	kg t^{-1}	25	5–20	6–8	medium	15–30
Dried poultry excrements	30	kg t^{-1}	55	5–30 (uric acid)	5	hidh	60–70
Sewage sludge (low DM)	1–2	kg m^{-3}	5	30–40	3–5	medium	45–55
Slurry (cattle)	4	kg m^{-3}	7.5	40–60	8	low	35–45
Biogas residue from plant biomass	2–3	kg m^{-3}	8	35–60	5–8	low	40–60
Biogas slurry with cofermentation	3–15	kg m^{-3}	5	45–70	2–5	low	50–70
Slurry (poultry)	10	kg m^{-3}	15	60–80	4	medium	70–85
Urine	4	kg m^{-3}	2	80–90	1–2	–	90–100

residues from biogas plants). Furthermore, maximum loads for organic fertilizers should be based not only on N loads, but also on C loads and expected humus reproduction from the added organic fertilizers (*Körschens* et al., 2004; *Gutser*, 2005).

As biogas technology is expected to become more important in the near future, farms without animal husbandry should give special attention to prevent an increase of N surplus at farm level. However, N from residues of biogas plants is very well suited for a synchronized application of N according to the plant demand during the growing season. Strategies to reduce NH_3 losses, split N applications, use of modern N stabilizers (*e.g.*, nitrification inhibitors), and realistic site-specific yield expectations should all be considered in order to fulfil the overall objectives of fertilizer application, *i.e.*, to simultaneously improve the N-use efficiency and to ensure environmental preservation.

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