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Liquid Cattle Manure Application to Soil and Its Effect on Crop Growth, Yield, Composition, and on Soil Properties

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1. Introduction

Soil application of liquid cattle manure (LCM) (excrements plus urine, occasionally containing bedding material) can enhance plant growth and increase crop yield (Beauchamp, 1986; Culley et al., 1981; Evans et al., 1977; Kaffka & Kanneganti, 1996; Lithourgidis et al., 2007; Matsi et al., 2003; Motavalli et al., 1989; Sutton et al., 1986; Zhang et al., 2006; Zebarth et al., 1996). In most of the cases, crop yield increases are accompanied by increases in plant macronutrients concentration and/or uptake (Culley et al., 1981; Lithourgidis et al., 2007; Matsi et al., 2003; Motavalli et al., 1989; Sutton et al., 1986).

The beneficial effect of LCM on crop growth, yield and macronutrients absorption is mainly due to the improvement of soil fertility with respect to macronutrients, especially N. In general, the amounts of readily available N in manures, mainly in the form of NH_4-N, are lower than that of the inorganic fertilizers (Beauchamp, 1983; Jokela, 1992). However, LCM contains high amounts of immediately available N, due to its urine content. The quantity of this immediately available N can be almost half of the total N and this percentage is higher than that of the solid cattle manure (Beauchamp, 1986; Bechini & Marino, 2009; Sutton et al., 1986). A significant amount of the ammoniacal N in LCM can be lost, as NH_3 by volatilization, shortly after LCM application to soils (Beauchamp et al., 1982; de Jonge et al., 2004; Pain et al., 1989; Pfluke et al., 2011a, 2011b; Webb et al., 2010). However, this depends on the properties of the LCM and soil, where manure is applied, and also on the rate, manner, timing of application and weather conditions and interactions among these factors (Beauchamp et al., 1982; Mannheim et al., 1995; Mattila et al., 2003; Pain et al., 1990; Reijs et al., 2007; Rochette et al., 2006; Sorensen, 1998; Thompson et al., 1990a, 1990b). Soil incorporation of LCM, mainly by using injection techniques, seems to reduce NH_3 volatilization drastically and such techniques are now applicable not only to arable soils but also to grasslands, no-tillage and forest systems (Maguire et al., 2011a, 2011b). Due to the high quantity of immediately available N, LCM can be as efficient as inorganic fertilizers in satisfying plant needs in respect to N, when it is applied at equivalent rates (Kaffka & Kanneganti, 1996; Lithourgidis et al., 2007; Matsi et al., 2003; Zhang et al., 2006). In addition to N, LCM can increase soil available P and K, upon its use as an organic fertilizer

(Beauchamp, 1983; Culley et al., 1981; Lithourgidis et al., 2007; Matsi et al., 2003; Pratt & Laag, 1981; Randall et al., 2000; Sutton et al., 1979, 1986; Zhang et al., 2006).

Apart from macronutrients, LCM contains also micronutrients, essential for plant growth. Therefore, it can serve directly as a source of micronutrients, upon its use as basal dressing for crops, increasing micronutrients plant uptake and probably concentration (Brock et al., 2006; Nikoli & Matsi, 2011). In addition, an indirect effect of LCM on the availability of the soil native micronutrients cannot be excluded. Application of the LCM to soil for a long period and/or at high rates can increase the soil organic matter especially the dissolved fraction (Antil et al., 2005a; Culley et al., 1981; Nikoli & Matsi, 2011), since a considerable part of the organic matter of manure (around 20 %) exists in its liquid phase (Japenga et al., 1992). Consequently, soil application of LCM can enhance solubilization of metal micronutrients through their complexation with the dissolved organic matter and consequently increase availability to plants (Japenga et al., 1992). Also, after use of LCM as a fertilizer for many years and/or at high rates, a possible improvement of the soil structure, due to organic matter increase, cannot be excluded (Olesen et al., 1997; Mellek et al., 2010).

Apart from the beneficial effects of using LCM as an organic fertilizer, certain adverse effects might be involved for plants, soils and the environment upon LCM application to soil; such as increasing salinity in the soil profile, NO_3-N leaching to the underground water and P accumulation in the top soil (with its subsequent translocation to surface water reservoirs) (Beauchamp, 1983, 1986; Comfort et al., 1987; Culley et al., 1981; Daliparthy et al., 1994; Evans et al., 1977; Heathwaite et al., 1998; Lithourgidis et al., 2007; Motavalli et al., 1985; Phillips et al., 1981; Pratt & Laag, 1981; Sutton et al., 1979, 1986; Vellidis et al., 1996). These adverse effects are mainly connected to LCM application for long periods and/or at high rates and such applications should be avoided. In addition, in certain cases, micronutrient phytotoxicities, especially of Cu and Zn are possible; these phytotoxicities, however, are associated mainly with LCM enriched with solutions used for cattle hoof baths (Bolan et al., 2003; Jokela et al., 2010; McBride & Spiers, 2001).

The objectives of this chapter are to compile and evaluate existing research and knowledge concerning: a) composition of LCM and its application to soil, with emphasis on N, b) effect of LCM application on crop growth, yield and composition, c) beneficial effects of LCM application on soil properties, especially fertility, d) possible risks, of using LCM as a fertilizer, for plants, soils and the environment. In addition, the Greek experience with long-term use of LCM as a fertilizer is discussed.

2. Liquid cattle manure composition and application to soil, with emphasis on N

Liquid cattle manure composition depends on certain factors, such as the number and age of animals, the ration fed to animals, the inclusion of bedding material and cleaning water, the duration and conditions of storage and the kind of treatment prior to soil application (Marino et al., 2008; Reijs et al., 2007; Sorensen, 1998). Selected cases of LCM composition, reported in the literature, are presented in Table 1. Among the elements contained in LCM, N is of major concern, in respect of using the LCM as an organic fertilizer efficiently, without causing adverse effects to the environment.

Weight basis	pH†	Dry matter‡	Total-N	NH_4-N	Total-P	Total-K	Reference
				g kg^{-1}			
wet	7.1-7.8	57-92	3.3-4.0	1.6-1.8			(Amon et al., 2006)
wet	6.7-6.8	49-60	2.3-2.7				(Angers et al., 2006)
wet		60-78	2.4-3.1		0.4-0.6	1.6-2.4	(Beauchamp, 1983)
wet		68-71	2.6-3.8	1.5-2.0			(Beauchamp, 1986)
dry		49-117	26-75	9-37			(Bechini & Marino, 2009)
wet	6.4-7.5	18-80	1.9-3.3	0.88-1.8	0.07-0.82		(Bittman et al., 2011)
dry	7.2±0.1		30±4.8		8.0 ± 0.1	32 ± 0.5	(Briceno et al., 2008)
dry	8.1	135	4.9		4.5	1.6	(Brock et al., 2006)
dry			38	16	3		(Burger & Venterea, 2008)
wet		98-101	3.0-3.4	1.4-1.6	1.2-1.4	2.5-3.0	(Carter et al., 2010)
wet	7.2-7.2	20-63	1.4-6.1				(Chadwick & Pain, 1997)
wet		111±15	4.1±0.5				(Chadwick et al., 2000a)
wet	5.7-7.0	60-110	2.6-3.2	0.93-1.6	0.39-0.53	2.0-3.1	(Comfort et al., 1987)
dry		88	29		7	24	(Culley et al., 1981)
dry	7.5±0.2	70 ± 4	53±0.8	25 ± 2			(de Jonge et al., 2004)
dry	7.6-8.1	104-107	73-79	41-56	23-40	13-59	(Evans et al., 1977)
wet	7.0-7.7	36-85	2.1-3.2	1.3-1.6			(Hansen et al., 2003)
dry	6.1-9.1	35-229	12-40	3.5-46	4.1-18		(He et al., 2004)
dry		190-239	21-29	6.7-13			(Jokela, 1992)
dry		71-88	49-53	19-22	9.5-11	36-48	(Kaffka & Kanneganti, 1996)
dry			4.3-31		3.7-8.4	45-17	(Lund et al., 1975)
wet	7.5±0.3	95 ± 32	3.8±1.0	1.5 ± 0.5	0.65±0.24	2.6 ± 0.8	(Marino et al., 2008)
wet	7.8-7.8	77-83	3.0-3.1	1.2-1.3	0.65-0.71	2.2-2.8	(Matsi et al., 2003)
wet	7.3-7.9	108-136	2.7-3.9	1.3-1.6	0.3-0.4	2.6-4.5	(Misselbrook et al., 1995)
wet	7.0-7.4	26-48	1.8-4.4	0.70-1.2			(Misselbrook et al., 1996)
dry	6.8-8.0	11-92		6.0-15			(Misselbrook et al., 2002)
wet		71-80	3.2-3.4				(Pain et al., 1986)
dry	7.6	103	46	27	12	60	(Pain et al., 1989)
wet	7.1-8.4		2.3-3.7	1.1-1.8			(Pain et al., 1990)
wet	6.2-6.6	56-62	2.9-3.4	1.7-2.4			(Paul & Beauchamp, 1993)
dry		82-131	33-78	13-48			(Reijs et al., 2007)
dry	7.2	101	31		7.1		(Siddique & Robinson, 2003)
wet	7.4-8.0	69-74	3.4-3.5	1.9-2.3			(Sorensen, 2004)
wet	4.9-6.5	64-91	2.4-3.5	0.6-1.7	0.4-0.7	1.7-3.5	(Sutton et al., 1979)
wet		45±19	1.8±0.6	0.7 ± 0.4	0.5±0.1	1.4±0.4	(Sutton et al., 1986)
wet	7.5-8.3	64-65	2.6-3.7	1.1-1.5			(Thompson et al., 1990a)
wet	8.3-8.4	65-86	3.2-3.9	1.4-1.8			(Thompson et al., 1990b)
wet		24-110	1.5-4.6	0.23-1.7			(Unwin et al., 1986)
wet		80-162	2.8-5.6	0.72-2.4			(Whitehead et al., 1989)
dry		35-72	55-61		11-14		(Withers et al., 2001)
wet			1.2		0.6	2.3	(Zhang et al., 2006)

† pH was measured directly in LCM or in a suspension with water.
‡ In all cases dry matter is expressed on wet weight basis.

Table 1. Some properties of liquid cattle manures (LCM), reported in the literature, with emphasis on the plant macronutrient concentrations (Values represent: mean values, mean values and their standard deviations, or ranges of mean values).

Liquid cattle manure contains high amounts of immediately plant available N, in the form of NH_4^+ (Bechini & Marino, 2009; Sorensen, 2004) as it is shown in Table 1, due to its urine content. For example, Bechini & Marino (2009) and Sorensen (2004) found that NH_4-N content of the LCMs studied ranged from 33 to 55 % and 50 to 60 % of the total N, respectively usually, LCM contains higher levels of immediately plant available N than the solid cattle manure (Beauchamp, 1986; Sutton et al., 1986). Beauchamp (1986) found that on average the NH_4-N was 53 % of the total N in LCM and 9 % in solid beef cattle manure. However, a high amount of this NH_4-N can be lost through NH_3 volatilization or immobilized after LCM addition to soil (Burger & Venterea, 2008; Pain et al., 1990; Sorensen & Jensen, 1995). The organically bound N in LCM is expected to mineralize slowly and provide less plant available N than solid cattle manure (Burger & Venterea, 2008). Chadwick et al. (2000a) reported that from fifty manures analyzed, in order to characterize their N fractions and assess their potential organic N supply, the percentage of N mineralized was the lowest for a dairy cow slurry (< 2 %), whereas for a beef cattle manure was about 6 %.

Nitrogen in LCM is subjected to certain changes during the storage, i.e. mineralization, microbial immobilization, NH_3 volatilization, nitrification and denitrification (Whitehead & Raistrick, 1993a). During storage, N transformations depend on the properties of the LCM, such as dry matter content, C/N ratio and pH, the inclusion of bedding material in the LCM and the period and conditions of storage (Amon et al., 2006; Sorensen, 1998; Whitehead & Raistrick, 1993a). Nitrogen losses consist mainly of emissions of NH_3 and N_2O. In order to reduce N gases but also other gases emissions, Amon et al. (2006) evaluated different treatments of dairy cattle slurry during storage, such as slurry separation, anaerobic digestion, slurry aeration and straw cover, in comparison to no treatment. They reported that the anaerobic digestion of the slurry during storage reduced greenhouse gasses emissions, without increasing NH_3 emissions compared to the untreated slurry, whereas all other slurry treatments increased NH_3 emissions. The acidification of cattle slurry to pH 5 and the addition of nitrification inhibitors have also been suggested for the reduction of N losses, prior to slurry application to soil (Pain et al., 1990).

After LCM application to soil, its N can be subjected to the same changes just mentioned, but also to others after its mineralization, i.e. retention to clay minerals in exchangeable form, fixation by clay, uptake by plants, leaching (Bechini & Marino, 2009). Nitrogen losses after soil application of LCM consist of N_2O and NH_3 emissions and NO_3^- leaching. However, the main losses of LCM N seemed to occur through NH_3 volatilization (Carter et al., 2010), which is expected to be higher in LCM than in solid cattle manure, because of the higher urine and consequently urea content of the former (Whitehead & Raistrick, 1993b). Ammonia volatilization usually occurs within a short period, after LCM surface application to soil, ranging from a few hours to a few days, with the greatest NH_3 emissions occurring within a few hours after application (Beauchamp et al., 1982; de Jonge et al., 2004; Pain et al., 1989; Pfluke et al., 2011a, 2011b; Webb et al., 2010). At this stage, N transformations and losses depend not only on the properties, storage conditions and treatments during storage of the LCM, but also depend on soil characteristics, the rate, manner and timing of LCM application to soils, the weather conditions and the interactions of these factors (Beauchamp et al., 1982; Mannheim et al., 1995; Mattila et al., 2003; Pain et al., 1990; Reijs et al., 2007; Rochette et al., 2006; Sorensen, 1998; Thompson et al., 1990a, 1990b).

Among the properties of the LCM, that most affects N transformations, after application to soils, is the C/N ratio. Slurries with a low C/N ratio are expected to promote N mineralization, whereas slurries with high C/N ratios are expected to promote N immobilization (Chadwick et al., 2000a). Also, Whitehead et al. (1989) reported that the water-insoluble material of cattle slurries immobilized N that would otherwise have been plant available from the whole slurries and/or the soil. This was attributed to the higher C/N ratio of the water-insoluble fraction of the cattle slurries compared to the whole slurries. In addition, they concluded that the fine particle size fractions of the water-insoluble material of the slurries had the greatest effect on N mineralization-immobilization. Another property that affects NH_3 volatilization from LCM applied on the soil surface is the dry matter content of the LCM (Braschkat et al., 1997; Dell et al., 2011; Misselbrook et al., 2005). It seems that as the dry matter content of LCM increases the viscosity of the material also increases. The result is that smaller amounts of NH_4^+ in LCM can infiltrate and be retained by soil components and in this way be preserved from loss, through NH_3 volatilization (Braschkat et al., 1997). The strong effect of dry matter content on NH_3 losses after LCM addition to soils was also reported for grasslands and arable soils by Pain et al. (1989) and Sommer & Olesen (1991). Finally, Thompson et al. (1990b) found an inverse relationship between cattle slurry application rate and the proportion of NH_4-N volatilized, after cattle slurry applied to grassland.

Soil properties, that affect LCM N transformations, after its soil application, seem to be pH, texture and water regime, along with land use, cultivation practices and weather conditions. Ammonia volatilization is expected to be reduced after LCM application to acid soils compared to calcareous soils (Bechini & Marino, 2009). Thompson et al. (1990a) reported that the total loss of NH_4-N, through NH_3 volatilization, from cattle slurry applied to grassland was approximately 1.5 times that from slurry applied to bare soil. Sommer & Ersboll (1994) reported that harrowing the soil before cattle slurry application reduced NH_3 volatilization, whereas de Jonge et al. (2004) found no significant effect. Bechini & Marino (2009) reported that nitrification and NO_3^- production was extremely rapid after LCM application on unsaturated soils, regardless of soil texture. Loro et al. (1997) and Lowrance et al. (1998) reported that denitrification and N_2O production after soil application of LCM was positively correlated with the soil water content and the cumulative production of N_2O was found to be higher for the solid than the liquid cattle manure (Loro et al., 1997). Rochette et al. (2008) found no differences between LCM and solid cattle manure in respect to N_2O emissions and reported that the N_2O emissions were affected by soil texture in conjunction to weather conditions. Soil texture also may influence the LCM NH_4-N immobilization; it was found that the net immobilization of N due to soil application of cattle slurry was increased with increasing soil clay content (Sorensen & Jensen, 1995). In addition, the same soil property along with the weather conditions seems to strongly affect LCM decomposition after its application to soil (Bechini & Marino, 2009; Rochette et al., 2006). Also after LCM application to soil, NH_3 volatilization tends to be increased with temperature and pH and suppressed temporarily by rainfall (Beauchamp et al., 1982; Sommer & Olesen, 1991) and N_2O emissions were found to be lower in the dry than in wet season (Chadwick et al., 2000b).

In order to reduce NH_3 emissions, but also nutrient losses in runoff, and increase N utilization by plants after LCM addition to soils, soil incorporation of the LCM is needed and for this purpose various application (mainly injection) techniques are proposed in the literature. Numerous researchers (Beauchamp, 1983; Beauchamp et al., 1982; Carter et al, 2010; Dell et al., 2011; Hansen et al., 2003; Maguire et al., 2011a, 2011b; Mannheim et al., 1995; Mattila & Joki-Tokola, 2003; Mattila et al., 2003; Misselbrook et al., 2002; Pfluke et al., 2011a, 2011b; Powell et al., 2011; Ross et al., 1979; Webb et al., 2005, 2010) agree that soil incorporation of LCM as soon as possible after its application or LCM surface banding or injection are preferable than the conventional surface broadcast application, for arable land but also for grassland, no-tillage and forage systems, although in the latter cases, using injection techniques, there is the possibility of grass sward damage and soil disturbance (Mattila et al., 2003). However, Laws et al. (2002) reported that shallow disc injection and, in particular, trailing shoe application of cattle slurry to grassland improved silage quality and reduced herbage contamination, without damaging it (except of the case of LCM injection on tall swards) compared with the conventional surface broadcasting. They suggested that shallow injection should be used on short swards wherever is possible, preferably after cutting, whereas slurry can be applied by trailing shoes on taller swards. In addition, Maguire et al. (2011a, 2011b) reported many techniques that facilitate the incorporation of liquid manures into the soil with restricted or minor soil disturbance, such as shallow disk injection, chisel injection, aeration infiltration and pressure injection.

Certain cases of increasing N_2O emissions (Comfort et al., 1990; Dell et al., 2011; Flessa & Beese, 2000; Thompson et al., 1987; Webb et al., 2010) due to the use of reduced-NH_3 emission application techniques (mainly injection) are reported in the literature. However, such increases are probably not inevitable and N_2O emissions can be reduced by slurry injection to such depths that will increase the diffusion path to soil surface sufficiently, leading to the emission of most nitrified N as N_2 (Webb et al., 2010). Furthermore, Powell et al. (2011) and Pfluke et al. (2011b) reported that injection of dairy slurry reduced not only NH_3 emissions but also NO_3^- leaching compared to surface broadcast application or surface broadcast application followed by partial incorporation of the slurry. On the other hand, it is reported that soil incorporation of LCM can promote LCM NH_4-N immobilization compared to surface banding (Sorensen, 2004).

A general rule that could be followed in order to reduce the overall N losses from LCM applied to soil and to increase plant efficiency utilization of LCM N, is the application of the LCM as close as possible to the period of maximum crop uptake (Bechini & Marino, 2009).

3. Effect of liquid cattle manure application on growth, yield and composition of crops

The beneficial effect of using LCM as an organic fertilizer on the yield of various crops has been proven by means of field experiments. Selected experiments are presented in Table 2 and discussed in this section. As one can see from Table 2, there is a large variety of LCM application rates, even within the same crop. This could be attributed to differences in composition of the cattle slurries used, but also to the different application approaches regarding the expected amount of LCM N that would be available for plant uptake during the growing season.

Generally, the application rates of the LCM are chosen on the basis of its N content. However, for reasons mentioned in the previous section, it is difficult to determine precisely the amount of the initial available NH_4-N of the LCM that will be lost from the soil or immobilized, or the percentage of the initial organically bound N of the LCM that will be mineralized and become available for plant uptake, or even the extent of the LCM influence on the transformations of the soil native N, during the growing season. Because crop availability of N in LCM is expected to be lower than that from inorganic fertilizers (Beauchamp, 1983; Jokela, 1992), greater LCM N rates were applied in comparison to N inorganic fertilizers (Beauchamp, 1983; Evans et al., 1977; Sutton et al., 1986; Zebarth et al., 1996). Such LCM application rates resulted in increased crop yields at levels similar to the inorganic fertilizers. However, the same was evident when LCM was applied at rates equivalent to the recommended inorganic N fertilization for crops, based on LCM total N content (Kaffka & Kanneganti, 1996; Lithourgidis et al., 2007; Matsi et al., 2003; Zhang et al., 2006). In addition, there are cases of applying cattle slurry at rates equivalent to the recommended inorganic N fertilizers, based on LCM initial plant available N content (Patni & Culley, 1989; Randall et al., 2000), or on this plus the expected amount of organically bound N that would be mineralized during the growing season (Beauchamp, 1986; Griffin et al., 2002). In both cases, the obtained crop yields, N uptake and recovery, as well as other plant parameters gave lower and more variable responses compared to inorganic fertilizers.

Increased crop yields upon LCM application to soil are usually accompanied by increases in plant uptake of macronutrients. Many researchers reported that N, P and K uptake of different plant species were increased, upon repeated annual applications of LCM for certain years, at levels similar or higher than the inorganic fertilization (Culley et al., 1981; Lithourgidis et al., 2007; Matsi et al., 2003; Motavalli et al., 1989). However, Motavalli et al. (1989) reported that although the N, P and K uptake by corn plants was increased with increasing application rate of injected dairy cow slurry, at levels similar to inorganic N, P and K fertilization, crop recoveries of fertilizer N, P and K were generally higher than those of slurry total N, P and K. In addition, Paul & Beauchamp (1993) found that N recovery by the harvested portion of the corn (grain + stover) was higher for urea than for LCM treatments. This was attributable to several possible causes, including: a) lower availability of organically bound nutrients in LCM, b) higher quantities of nutrients applied with the LCM, c) differences in nutrient placement and d) greater loss of nutrients from the LCM treatments (Motavalli et al., 1989).

The beneficial effect of LCM application to soil on macronutrient concentrations in plant tissues is not apparent (Evans et al., 1977; Lithourgidis et al., 2007; Matsi et al., 2003; Parsons et al., 2007; Sutton et al., 1986). Sutton et al. (1979, 1986) reported that LCM did not consistently increase corn leaf N and P and Matsi et al. (2003) reported that N, P and K in the aboveground biomass of wheat remained unchanged upon LCM or inorganic fertilization application, whereas Evans et al. (1977) found that LCM, relative to the unfertilized and inorganic fertilized treatments, increased the N, P and K concentrations in corn ear leaves, grain and stover. The same was reported by Lithourgidis et al. (2007) for the three macronutrients in the aboveground biomass of corn at the R3 growth stage. This was probably due to the different application period and rates of LCM.

The beneficial effect of soil application of the LCM on micronutrient concentrations in plant tissues and uptake by plant species is ambiguous. In any case, increases of these plant parameters are expected after repeated annual applications of LCM to soil for many years and/or at high rates (Evans et al., 1977; Nikoli & Matsi, 2011).

LCM application rates	Plant species	Years	Reference
67-269 kg ha^{-1} yr^{-1} as N 70-560 kg ha^{-1} yr^{-1} as N	Corn (*Zea mays* L.)	3 3	(Beauchamp, 1983)
100-600 kg ha^{-1} yr^{-1} as N	Corn	3	(Beauchamp, 1986)
200-400 kg ha^{-1} yr^{-1} as N	Tall fescue (*Festuca arundinacea* Schreber)	6	(Bittman et al., 2011)
25-50 m^3 ha^{-1}, 3-4 times per yr	Orchardgrass (*Dactylis glomerata* L.) Reed canarygrass (*Phalaris arundinacea* L.)	2 2	(Carter et al., 2010)
53-138 Mg ha^{-1} yr^{-1}	Corn	3	(Comfort et al., 1987)
224-879 kg ha^{-1} yr^{-1} as N	Corn	5	(Culley et al., 1981)
94-199 m^3 ha^{-1} yr^{-1}	Potato (*Solanum tuberosum* L.)	3	(Curless et al., 2005)
112 & 336 kg ha^{-1} yr^{-1} as N	Alfalfa (*Medicago sativa* L.)	2	(Daliparthy et al., 1994)
224 metric tons ha^{-1} yr^{-1}	Corn	2	(Evans et al., 1977)
84 & 56 kg ha^{-1} as N	Mixed forage species	6	(Griffin et al., 2002)
240 kg ha^{-1} yr^{-1} as N	Corn	3	(Jokela, 1992)
150-450 kg ha^{-1} yr^{-1} as N	Orchardgrass	2	(Kaffka & Kanneganti, 1996)
80 Mg ha^{-1} yr^{-1}	Corn	4	(Lithourgidis et al., 2007)
45-135 metric tons ha^{-1} yr^{-1}	Coastal bermudagrass (*Cynodon dactylon* L.)	3	(Lund et al., 1975)
100-300 kg ha^{-1} yr^{-1} as N	Corn	3	(McGonigle & Beauchamp, 2004)
40 Mg ha^{-1} yr^{-1}	Winter wheat (*Triticum aestivum* L.)	4	(Matsi et al., 2003)
33-62 Mg ha^{-1} yr^{-1}	Meadow fescue (*Festuca pratensis* Huds), timothy [*Phleum pretense* (L.) Trabud] Timothy	3 3	(Mattila et al., 2003)
53-138 Mg ha^{-1} yr^{-1}	Corn	2	(Motavalli et al., 1989)
60 kg ha^{-1} yr^{-1} as N	Rye grass (*Lolium perenne* L.), white clover (*Trifolium repens* L.)	2	(Misselbrook et al., 1996)
80-160 kg ha^{-1} yr^{-1} as N	Herbage	3 (27 sites)	(Pain et al., 1986)
32.1-64.3 Mg ha^{-1}	Corn, wheat, soybean [*Glysine max* (L.) Merr]	2	(Parsons et al., 2007)
90 Mg ha^{-1} yr^{-1}	Corn	3	(Patni & Culley, 1989)
100-300 kg ha^{-1} yr^{-1} as N	Corn	3	(Paul & Beauchamp, 1993)
75 m^3 ha^{-1} yr^{-1}	Oat (*Avena sativa* L.), corn, winter rye (*Secale cereale* L.)	4	(Powell et al., 2011)
21 & 42 metric tons ha^{-1} yr^{-1}	Barley (*Hordeum vulgare* L.), sudangrass (*Sorghum sudanese* L.)	4	(Pratt & Laag, 1981)
154-224 kg ha^{-1} yr^{-1} as N	Corn	4	(Randall et al., 2000)
112-336 Mg ha^{-1} yr^{-1}	Corn Alfalfa, orchardgrass	3 2	(Sutton et al., 1979)
112-336 Mg ha^{-1} yr^{-1}	Corn	6	(Sutton et al., 1986)
75 m^3 ha^{-1}	Rye grass	3 (7 trials)	(Unwin et al., 1986)
175-525 kg ha^{-1} yr^{-1} as N	Corn	2	(Zebarth et al., 1996)
100 & 200 kg ha^{-1} as N	Smooth bromegrass (*Bromus inermis* Leyss) Oat	3 3	(Zhang et al., 2006)

Table 2. Field experiments: liquid cattle manure (LCM) application rates, the plant species studied and the duration of the experiment.

Because of the higher levels of the readily available N in LCM than in solid cattle manure (Beauchamp, 1986; Sutton et al., 1986), LCM seems to a be more effective organic fertilizer than solid cattle manure, when applied at equivalent N rates (Beauchamp, 1986; Kaffka & Kanneganti, 1996; Lund et al. 1975; Paul & Beauchamp, 1993; Zhang et al., 2006). Beauchamp (1986) reported that crop yield responses were higher in the LCM than the solid cattle manure treatments and the same is reported by Lund et al. (1975), Kaffka & Kanneganti (1996) and Zhang et al. (2006). In addition, Kaffka & Kanneganti (1996) found that N uptake by plants grown in plots that had received LCM was higher than the plots that had received solid cattle manure and Paul & Beauchamp (1993) found that N recovery by the harvested portion of the corn (grain + stover) was higher for LCM than for solid beef manure treatments. However, Evans et al. (1977) found that upon both manures application, crop yields increased significantly compared to control, at levels similar to the inorganic fertilization, and this could be attributed to the heavy application rates of both manures but also to the different application rates. Also, Evans et al. (1977) reported a residual beneficial effect of both manures on crop yield for two years, whereas Zhang et al. (2006) reported the same effect but only for LCM, although the opposite was expected, since solid cattle manure contains more organically bound N than LCM, which could be available for plant uptake after its mineralization for a longer period. In addition, Sutton et al. (1986) found that corn yields were increased the following year, after LCM application for five years at high rates. Surprisingly, Beauchamp (1987) reported that corn response to residual N from animal manures, including LCM and solid beef manure, after two years from application, was lower than that obtained for urea, the first year following the two years of application. However, the second year, following the two years of application, there was only a small response to residual N from any of the sources, organic or inorganic.

4. Effect of liquid cattle manure application on soil properties

The beneficial effect of LCM on crop yields has been connected to the improvement of soil fertility mainly, after LCM application to soils. In addition, a possible improvement of soil physical properties, through the increase of soil organic matter due to LCM application, cannot be excluded in the cases of long term and/or heavy applications. However, there are certain risks involved for plants, soils and the environment following LCM application to soils, such phytotoxicity of micronutrients, nutrient losses from soil by leaching and/or in the runoff and increase of soil salinity to unacceptable levels. All these aspects are discussed in this section.

Upon the use of LCM as an organic fertilizer for crops, soil availability of the plant macronutrients N, P and K is expected to be increased and maintained at desirable levels, when LCM is applied at optimal rates (Beauchamp, 1983; Culley et al., 1981; Lithourgidis et al., 2007; Matsi et al., 2003; Pratt & Laag, 1981; Randall et al., 2000; Sutton et al., 1979, 1986; Zhang et al., 2006). On the other hand, there are certain risks of plant macronutrients accumulation in the soil and their subsequent losses to the underground water or to surface water reservoirs (Misselbrook, et al., 1995; Soupir et al., 2006). These risks are more pronounced in the case of LCM application at high rates and/or for a long period. Such risks are mainly the NO_3^- loss below the root zone due to leaching and P accumulation in the top soil and its subsequent loss in the runoff (Culley et al., 1981; Evans et al., 1977; Pratt & Laag, 1981; Sutton et al., 1979, 1986; Vellidis et al., 1996), although also NO_3^- loss in the runoff and P leaching cannot be excluded. However, it is uncertain if these risks are greater in the case of LCM application than when applying inorganic fertilizers (Beauchamp, 1983, 1986; Comfort et al., 1987; Daliparthy et al., 1994; Heathwaite et al., 1998; Lithourgidis et al., 2007; Motavalli et al., 1985, Phillips et al., 1981; Randall et al., 2000).

In addition to gaseous N losses following LCM application to soils, reported in the second section of this chapter, N can be lost as NH_4-N associated with suspended soil particles in the runoff (Smith et al., 2001a), but the main loss is through NO_3^- leaching. The LCM N (the inorganic NH_4-N or the organically bound N, after its mineralization) can be readily transformed to NO_3-N, which is highly soluble and thus it is susceptible to leaching. Indeed, many researchers found elevated concentrations of NO_3^- in the soil profile upon LCM application. However, these increased concentrations were at similar or lower levels than those caused by the inorganic fertilizers, especially urea, applied at rates equivalent or even lower than the LCM N (Beauchamp, 1983, 1986; Comfort et al., 1987; Daliparthy et al., 1994; Jokela, 1992; Lithourgidis et al., 2007; Motavalli et al., 1985; Phillips et al., 1981; Randall et al., 2000). For example, Phillips et al. (1981) reported that NO_3-N concentration in the tile-drain effluent from silage corn receiving LCM at a rate of 897 kg N ha^{-1} was no greater than that from 134 kg N ha^{-1} applied as inorganic fertilizer. Beauchamp (1983) found that 560 kg N ha^{-1} as LCM resulted in less soil NO_3-N than 208 kg N ha^{-1} as urea and Beauchamp (1986) reported that application of LCM at a rate of 600 kg N ha^{-1} did not increase soil NO_3-N levels above those from urea or the lower LCM application rates.

As far as P concerns, the major problem seems to be P build-up in the plow layer and loss in the runoff following LCM application to soil (Smith et al., 2001b; Soupir et al., 2006), because usually P is strongly associated to soil particles or exist in the form of insoluble substances in the soil and thus it moves down the soil profile with difficulty. However, the P leaching cannot be excluded (Pratt & Laag, 1981; Tarkalson & Leytem, 2009), since appreciable amounts of water soluble P can be found in the LCM (Kleinman et al., 2005). Again, P accumulation in the upper soil layer was found after LCM applications for many years and/or at high rates (Culley et al, 1981; Pratt & Laag, 1981; Sutton et al., 1986). Furthermore, it is questionable if the risk of P build-up following soil LCM application is greater than that from inorganic fertilizers (Withers et al., 2001). Phosphorus in LCM treated soils was found to be less available than in soils treated with triple superphosphate (Withers et al., 2001); however, Siddique & Robinson (2003) and Tarkalson & Leytem (2009) reported that P availability and mobility in LCM treated soils were higher than in soils treated with potassium di-hydrogen phosphate or mono-ammonium phosphate, respectively.

The effect of soil application of the LCM on the availability of plant micronutrients has not been investigated adequately in the literature, probably because this effect is inconsistent, even after repeated LCM applications for many years. However, the concentration of soil available micronutrients is likely to be increased after long-term repeated applications of LCM (Brock et al., 2006; Nikoli & Matsi, 2011). In certain cases, the risk of Cu and Zn phytotoxicities is possible upon soil application of enriched LCM with metals. The causes of such enrichments are the use of Cu and Zn feed additives to cattle and mainly the addition of hoof treatment solutions containing $CuSO_4$ or $ZnSO_4$ to the manure storage (Bolan et al., 2003; Jokela et al., 2010; McBride & Spiers, 2001). In order to clarify this risk, Brock et al. (2006) studied the accumulation, depth distribution and bioavailability of Cu and Zn in 109 fields, amended with LCM for 5 to 40 years. They found increased soil total Cu and Zn concentrations in the plow layer, but Cu and Zn soil available concentrations were low and the same was evident for Cu and Zn concentrations in the leachates collected from soil cores (0-50 cm). They concluded that there was no evidence that Cu and Zn accumulation in the plow layer had reached toxicity thresholds, even after 40 years of LCM application.

Increases of soil total organic C and N resulting from cattle manures application to soils are mainly connected to the addition of solid cattle manure (Chang et al., 1991; Eghball, 2002) than LCM, due to the higher dry matter content of the former in comparison to the latter (Sutton et al., 1986). Consequently, since LCM contains low amounts of dry matter and thus low amounts of organic matter, the beneficial effect of LCM application on soil total organic C and N becomes apparent after many years of continuous application and/or at high rates (Antil et al., 2005a, 2005b; Culley et al., 1981; Nikoli & Matsi, 2011). Culley et al. (1981) found that soil total organic C increased significantly upon LCM application at high rates, for 5 years. Nikoli & Matsi (2011) reported that soil total and dissolved organic C increased significantly after nine years of LCM addition to soil, at rates equivalent to the recommended inorganic fertilization for crops. At that time, no significant increase of soil total N was evident. Significant increases of both total organic C and N in the top soil were also reported, after addition of cattle slurry in fallow and cropped plots, for 28 and 38 years, respectively (Antil et al., 2005a, 2005b). On the other hand, Mellek et al. (2010) observed a tendency for increases in soil total organic C due to LCM application to a no-tillage soil for only two years and Briceno et al. (2008) reported that LCM application at rates of 100-300 m^3 ha^{-1} to a soil with high initial content of organic matter, although it did not increase total organic C, resulted in increased dissolved organic C immediately after addition. Angers et al. (2006), who studied the dynamics of soil dissolved organic C following application of LCM to a loamy and a clay soil, reported that their results were inconsistent and the overall, temporal variations in soil dissolved organic C content were large and greater than the fluctuations directly attributable to LCM addition.

The impact of LCM application on soil physical properties has not been adequately investigated in the literature. However, because improved soil properties are strongly connected to increased soil organic matter content, in addition to other soil properties that also influence soil structure, the improvement of soil physical properties due to LCM application is expected after long-term continuous applications of LCM and/or at high rates. Olesen et al. (1997) reported that water holding capacity of two soils differed in texture increased after addition of LCM at rates of 15-20 % and Mellek et al. (2010) found that application of LCM in a no-tillage soil for two years improved soil structure by changing physical properties, such as bulk density, macroporosity, aggregates mean weight diameter, saturated hydraulic conductivity and water infiltration rate.

Although the beneficial effect of LCM application on soil properties is adequately established in the literature, there are cases of questioning this effect. Jokela et al. (2009) reported that LCM application to soil at a rate of 110 m^3 ha^{-1} yr^{-1}, for four years did not improve soil quality. This was attributed to removal of the large particle-size solids from the LCM prior its use to the field, as well as to the fact that the experimental field was in no-tillage production with various crop rotations and had received periodic application of manure for twenty years before the experiment.

The risk of increased soil salinity at unacceptable levels and consequently the risk of possible plant injury are possible after repeated heavy applications of LCM (Culley et al., 1981; Evans et al., 1977; Sutton et al., 1979, 1986). However, it is uncertain if this risk is greater than that due to the use of inorganic fertilizers. Evans et al. (1977) and Sutton et al. (1979) reported that soil salinity increased significantly, upon application of LCM at rates up to 336 metric tons ha^{-1} yr^{-1}, but remained at levels below the critical limit, even at the highest application rate. Lithourgidis et al. (2007) found increased salinity in the soil profile after eight years of LCM application to soil, at rates equivalent to the recommended inorganic fertilization for crops, but at levels acceptable for most crops and similar to the levels caused by the inorganic fertilization. Pratt et al. (1977), who studied salts leaching as a function of application rates of solid and liquid cattle manures and irrigation systems, reported that large amounts of K, Ca and Mg were accumulated in the soil, but there was a net loss of Na. The percentage of leached cations coming from manures declined as the application rate of manures increased. They suggested that, under most irrigation systems, addition of manures to fine-textured soils can result in a reduction of salts leaching to underground water compared to coarse-textured soils, due to their lower infiltration rate.

As far as the soil pH concerns, LCM application to soils at high rates or at rates equivalent to the recommended inorganic fertilization for crops for many years is not expected to affect it (Briceno et al., 2008; Nikoli & Matsi, 2011). Briceno et al. (2008) reported that soil pH increased immediately on addition of LCM at high rates to soils but returned to values similar to control and Nikoli & Matsi (2011) found that soil pH remained unchanged after nine annual applications of LCM, at rates equivalent to the recommended inorganic fertilization for crops.

5. The Greek experience of using liquid cattle manure as a fertilizer

The effect of LCM application to soil on wheat and corn and soil properties was studied in comparison to commercial inorganic fertilizers (both applied at equivalent N-P recommended rates), by means of a field experiment, in Northern Greece (Dordas et al., 2008; Lithourgidis et al., 2007; Matsi et al., 2003; Nikoli & Matsi, 2011).

The experiment was established in a field of the Farm of Aristotle University of Thessaloniki (22°, 59′, 6.17′′ north latitude and 40°, 32′, 9.32′′ east longitude), the fall of 1996. Field soil was a calcareous loam (Typic Xerorthent) (Matsi et al., 2003) and cultivated with winter wheat for four years, remained uncultivated for one year and then cultivated with corn until 2011. The size of the experimental plots was 60 m^2 and the experimental design was completely randomized blocks with six replications.

The fertilization treatments (Lithourgidis et al, 2007; Matsi et al., 2003) were established in the same plots each year and were: a) Soil incorporation of LCM, before sowing; b) application of the recommended for each crop N-P inorganic fertilization, as a single basal dressing, before sowing; c) application of the recommended for each crop N-P inorganic fertilization, but with split application of the N inorganic fertilizer, half of the amount as basal dressing before sowing and the other half at a specific growth stage of the crop (at tillering for wheat, broadcast and at the V8 growth stage for corn, as side dressing); d) no organic or inorganic fertilization (control).

The LCM was collected in an open tank, occasionally agitated during storage and diluted with water to obtain density of almost 1 g mL^{-1} prior its use for the field experiments. Analysis of the LCM composition was performed for three consecutive years prior to 1996 and repeated during the first two years of the wheat experiment. The results showed that

LCM properties were almost constant over the years, in respect to pH, dry matter content and N and P concentrations. Potassium concentrations were affected by the ration composition (unpublished data). Consequently, the mean values of total N and P contents of manure (Matsi et al., 2003)(Table 1) were taken as the basis for LCM application rates, for both experiments with wheat and corn and LCM was applied at 40 and 80 Mg ha^{-1} yr^{-1} (wet weight basis), for wheat and corn, respectively. The recommended N-P inorganic fertilization consisted of 120 kg N ha^{-1} yr^{-1} and 26 kg P ha^{-1} yr^{-1}, for wheat and of 260 kg N ha^{-1} yr^{-1} and 57 kg P ha^{-1} yr^{-1}, for corn (with single or split application of the N fertilizer). Fertilizers (inorganic or LCM) were applied a few days before wheat or corn sowing and incorporated into the soil as soon as possible (Lithourgidis et al, 2007; Matsi et al., 2003).

Each year, plant samples were collected at two specific growth stages of the crops and analyzed for nutrients; the first growth stage was the heading and the R3 growth stage, for wheat and corn, respectively and the second growth stage was the harvest for both crops. In addition, samples from the soil surface or deeper layers were collected and analyzed (Lithourgidis et al, 2007; Matsi et al., 2003; Nikoli & Matsi, 2011).

The results of the 4-yr (1996-2000) field experiment with winter wheat (Matsi et al., 2003) showed that application of the LCM to soil did not affect seed germination and N, P and K concentrations in plant tissues. However, upon LCM addition to soil, aboveground biomass of wheat, grain yield and plant uptake of the three macronutrients increased significantly compared to control, at levels similar to the inorganic fertilization. Similar increases were obtained for the available NO_3-N, P and K concentrations in the surface soil layer. After four years of LCM application to soil, there was no evidence of N, P and K build-up in soil, whereas soil salinity, organic C and total N levels remained unchanged.

The same beneficial effects of the LCM, as for wheat, were evident for corn in the first four years (2002-2005) of the corn experiment (Lithourgidis et al, 2007). Moreover, concentrations of the macronutrients N, P and K in the aboveground corn biomass, at the R3 growth stage increased significantly relative to control, at levels similar or higher that the inorganic fertilization treatments, in the years 2004 and 2005. As far as the soil properties, combining the results of the first four years corn experiment with those of the wheat experiment showed that, annual LCM application for eight years maintained the amounts of the available NO_3-N, P and K in the surface soil layer, at desirable levels, each year of the application period. Upon LCM addition to soil, available NO_3-N in the soil profile (0-90 cm) increased significantly compared to control, at levels similar to the commercial fertilizers. The same was evident for soil salinity, but in all cases salinity levels were acceptable for most crops. After eight years of annual LCM application to soil, soil organic C and total N remained unchanged.

During the same period (2002-2005), Dordas et al. (2008) measured dry matter accumulation and partitioning at silking and harvest, yield components, morphological characteristics, chlorophyll content and N uptake and partitioning and calculated N remobilization and use efficiency in corn. They reported that upon LCM application to soil, all properties increased significantly compared to control and were at levels similar to the inorganic fertilization treatments, in the years 2004 and 2005.

The beneficial effect of soil application of LCM on the availability of micronutrients was apparent after seven years of repeated LCM applications (Nikoli & Matsi, 2011). Although, the Cu, Zn, Fe, Mn and B concentrations in corn aboveground biomass, collected at the R3 growth stage, were not affected by fertilization, the uptake of micronutrients by corn grown on manured plots increased significantly compared to control and were at levels similar to inorganic fertilizer treatments, in the years 2005 and 2006. In addition, by 2007, i.e. after nine years of LCM addition to soil, the soil available micronutrients increased significantly and this increase was accompanied by increases in soil total and dissolved organic C.

Measurements of the plant and soil parameters performed after 2007 revealed that the beneficial impact of soil application of LCM on macro- and micronutrient concentrations in corn aboveground biomass, plant uptake and soil availability and on soil total and dissolved organic C was persistent (unpublished data). Also soil total N was increased, upon soil LCM application of LCM, but the C/N ratio remained unchanged (unpublished data). In addition, in 2009, i.e. eleven years of repeated annual LCM additions to soil, available NO_3-N and salinity in the soil profile (0-90 cm) were found to be significantly increased compared to control, but at levels similar or lower than the commercial fertilizers. In all cases, soil salinity levels were acceptable for most crops (unpublished data).

6. Conclusions

The use of liquid cattle manure (LCM) as an organic fertilizer for crops is based on the fact that LCM is a valuable source of plant nutrients, especially of N; since it contains high amounts of readily plant available NH_4-N, due of its urine content. Large percentages of this ammoniacal N can be lost during the storage of the LCM, but especially after LCM application to soils through NH_3 volatilization. For this reason, soil incorporation of the LCM is suggested as soon as possible after land application or even at the moment of application. For this purpose, many techniques and equipment have been developed recently for use on arable soils but also in grassland, no-tillage and forest systems.

The application rates of LCM to soil, which are based usually on its N content, can be variable, depending on the expected LCM N that will be available for plant uptake during the growing season. The quantification of LCM N transformations and losses after LCM application to soils seems to be a black box, even today. The problem is complex, since in addition to LCM properties, soil properties along with the weather conditions regulate these transformations and losses. When the LCM is applied to soils at rates higher than the recommended (in respect to N) inorganic fertilization rates for crops, it can enhance crop growth, yield and macronutrients uptake and maintain soil fertility at desirable levels. However, the same has been proven for soil application of the LCM at rates equivalent to the recommended inorganic fertilizers rates for crops, based on the total N content of the LCM.

The beneficial effect of soil application of the LCM on micronutrients availability in soil and plant uptake can become apparent only after a long-term continuous use of LCM as a fertilizer. The same is true and for its effect on soil organic matter and physical properties. This is probably the reason for the few relevant studies on these topics in the scientific literature.

The risk of increased soil salinity, NO_3^- leaching and P build-up in the top soil at unacceptable levels due to LCM application are connected mainly to repeated heavy application rates, which should be avoided anyway. However, in any case it is uncertain if this risk is greater from LCM than from inorganic fertilizers use. The risk of Cu and Zn phytotoxicites is connected to the use of LCM enriched with these metals, but again this fact has not been adequately established.

Overall, it can be concluded that soil incorporation of liquid cattle manure (LCM) at rates equivalent to the recommended inorganic fertilization rates for crops can enhance crop growth, yield and nutrient uptake and maintain soil fertility at desirable levels, without causing adverse effects to plants, soils and the environment.

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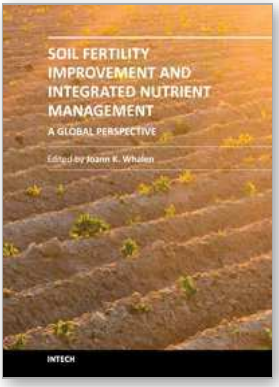

Soil Fertility Improvement and Integrated Nutrient Management - A Global Perspective

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Soil Fertility Improvement and Integrated Nutrient Management: A Global Perspective presents 15 invited chapters written by leading soil fertility experts. The book is organized around three themes. The first theme is Soil Mapping and Soil Fertility Testing, describing spatial heterogeneity in soil nutrients within natural and managed ecosystems, as well as up-to-date soil testing methods and information on how soil fertility indicators respond to agricultural practices. The second theme, Organic and Inorganic Amendments for Soil Fertility Improvement, describes fertilizing materials that provide important amounts of essential nutrients for plants.The third theme, Integrated Nutrient Management Planning: Case Studies From Central Europe, South America, and Africa, highlights the principles of integrated nutrient management. Additionally, it gives case studies explaining how this approach has been implemented successfully across large geographic regions, and at local scales, to improve the productivity of staple crops and forages.