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# Improving environmental performances of organic spreading technologies through the use of life cycle assessment

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## Abstract

Life Cycle Assessment (LCA) is generally used to assess environmental performances of a product or a system. Some agricultural LCA were carried out to assess environmental performances of fertilisation processes, but they barely take into account the direct contributions of agricultural machinery. In this paper, we develop the three step method used to assess the environmental impacts of organic spreading using the LCA approach in order to ecodesign organic spreaders (building technological indicators, establishing a link between these indicators and nitrogenous emissions, and assessing fuel consumption of tractors during all the spreading processes). We achieve a LCA study for 45 spreading scenarios and compare environmental performances of spreading machines according to the main LCA environmental impacts. LCA results mainly show that pedoclimatic conditions have an influence on the environmental impacts of spreading scenarios especially for acidification, eutrophication, and global warming and that environmental impacts present significant differences between spreading machines.

Key words: Spreading technology, environmental performances, LCA, sewage sludge, nitrogenous emissions.

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## Introduction

Most of the environmental impacts in agriculture are due to the emissions of chemicals such as nitrous oxide (N<sub>2</sub>O), ammonia (NH<sub>3</sub>) and nitrate (NO<sub>3</sub>). As they generate such substances, manures, sludges and to a lesser extent mineral fertilisers are often associated with environmental burdens and contribute to major environmental impacts (acidification, eutrophication and global warming). Concerns over these emissions have led to the assessment of the environmental impact of fertilisation processes (Brentrup et al., 2001; Brentrup et al., 2004; Pradel et Thirion, 2008) or to the reduction of these emissions through different application techniques, mainly for ammonia volatilisation (Hansen et al. 2003; Huijsmans et al., 1998; Misselbrook et al., 2002; Sandars et al., 2003; Smith et al., 2000; Sommer et al., 1997) and, to a lesser extent, for nitrate leaching and nitrous oxide emission (Ellis et al., 1998; Thomsen et al., 2005).

While many studies have focused on the mechanisms of emission production during land application linked with the type of effluent, very few studies take the technology used for spreading operation into account. However, in order to improve the environmental performances of spreading machines to reduce nitrogenous emissions, it is necessary to take an interest in the spreader technological characteristics that have a direct impact on these type of emissions and so on the environment. Eventually, this will allow a comparison between a 'classic' spreader and an 'ecodesigned' spreader and assess the environmental benefits of new prototypes.

This paper presents a comparison of the environmental impacts of sewage sludge spreading scenarios involving different types of spreaders in different pedoclimatic conditions using Life Cycle Assessment.

Life Cycle Assessment (LCA) is a common tool to assess environmental impacts of a product or a system. The process or product life cycle is assessed from raw material acquisition through production, use and disposal in a "cradle to grave" perspective. Each step of the life

cycle consumes energy, depletes non renewable resources and produces air, soil and water emissions at different scales (local, regional or global scale). According to ISO14040 standards (AFNORa, 2006; AFNORb, 2006), Life Cycle Assessment is conducted through a four step procedure including (i) goal and scope definition, (ii) life cycle inventory, (iii) life cycle impact assessment and (iv) interpretation.

## Materials and methods

### Goal and scope definition

The goal and scope definition step includes the description of the analysed system, the definition of system boundaries and the definition of an adapted reference unit called functional unit, representative of the system functions and to which all the inventory data should refer.

### Objectives of the study

The first objective of this study is to compare environmental impacts of sewage sludge spreading scenarios using different spreading technologies, thus having a better understanding of the environmental impacts of the different spreading operation steps (loading, transport, spreading).

The second objective is to highlight the environmental impacts of spreading machines according to their technological performances and to test whether the LCA method can discriminate environmental performances of spreading machines.

Finally, the LCA results of this study will be used to validate software called ACV3E<sup>1</sup> allowing a simplified environmental evaluation of spreading operations with the LCA tool.

### System boundaries

The system boundaries are quite difficult to evaluate because spreading operations may be considered part of both the crop management and the sewage sludge disposal route. As our study is focused on the spreader environmental performances, the system boundaries are limited to the spreading operation as shown in Figure 1.

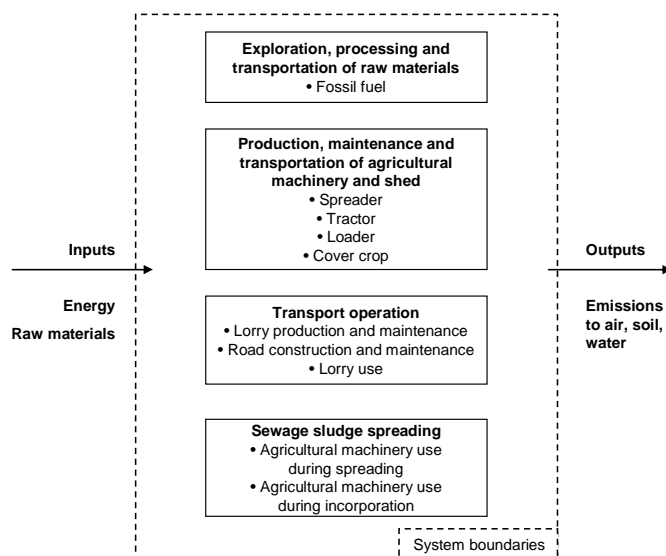


Figure 1: Description of the sewage sludge spreading operation boundaries

The system takes into account the logistic phase of the spreading operation, consisting of the transport operations of the sludge and the agricultural machinery. The filling up and loading part are also taken into account in the logistic phase. As cleaning of the spreading material is done once a year, this step is not included. In addition, the system takes also the spreading part itself into account, consisting in spreading in the field. Regarding legislation, sewage sludges are ploughed in 24 hours after spreading with a cover crop.

The inputs include the environmental impact of the agricultural machinery used for spreading operations, in both

logistic and spreading phases (manufacture and transport of agricultural machinery and shed, lorry transport operation), and the energy used for the agricultural machinery (fuel production). The outputs include emissions from the fuel combustion, for both tractor and

<sup>1</sup> In English, "ACV Evaluation Environnementale Epannage" means "Spreading environmental evaluation with LCA"

lorry, the tyre abrasion of the agricultural machinery and the nitrogenous emissions related to the sewage sludge application in the soil. Emissions during the storage (at waste water treatment plant and intermediate storage) are left out of the system.

All the sewage sludge production processes, such as the metallic trace elements (MTE) contained in the sludge and the energy used for the sludge treatment (thickening, dehydration...), are not taken into account in the system. These assumptions have been made because spreading operation has absolutely no interaction with a possible reduction of the MTE environmental impacts and the sludge production process. Nevertheless, the MTE significantly impact the ecotoxicity and toxicity categories and remain the main environmental problem of sewage sludge production (Hospido et al., 2005; Houillon, Jolliet, 2005; Suh, Rousseaux, 2002).

### **Functional unit**

Sewage sludge can be considered as a waste, as well as a fertiliser. If sludge is considered as a waste, the best functional unit will be the ton of sludge spread (dry or fresh matter). If sludge is considered as a fertiliser, the most suitable functional unit will be the quantity of nutritive element spread (N, P or K).

However, spreading sludge is subject to legislation and should respect a fertilisation plan. Agronomic value of sewage sludge should be known to best fit the crop needs. The most relevant functional unit for our system will, thereby, be the *dry matter ton of sewage sludge spread in the field, taking into consideration both the respect of legislation and an application rate calculated on the basis of the nutrient, which first fits the plant requirements.*

### **Scenario description**

As nitrogenous emissions can be variable depending on the pedoclimatic conditions, we studied five spreading operations into nine cropping systems (Pacaud et al., 2010). The frame of the 45 scenarios is described in Table 1. The application rates used for the functional unit and the reference flow setting up are shown in brackets. The cropping systems were chosen according to their sensitivity to different environmental risks and described in Pacaud et al. (2010). As shown in Table 1, all the scenarios related to KI1 and KI3 cropping systems or using a slurry tanker with injectors do not include the incorporation of the sludge, considering that our scenarios are based on realistic spreading operations. In the same manner, no spreading with a slurry tanker with injector can be assessed in KI1 cropping system, as spreading occurs while wheat is already sown. Thereof, only 44 spreading scenarios will be assessed with the LCA method.

Cropping systems	Pairing of spreading machine and sewage sludge				
	P1 as Slurry tanker – splash plate – liquid SS <sup>2</sup>	P2 as Slurry tanker – injector – liquid SS	P3 as Organic spreader – vertical moving rotors – solid SS	P4 as Organic spreader – vertical moving rotors – compost SS	P5 as Organic spreader – discs – pelleted SS
Mt1	S1 (1.85)	S10 (1.85)	S18 (5.26)	S27 (7.27)	S36 (1.62)
Mt2	S2 (1.85)	S11 (1.85)	S19 (5.26)	S28 (7.27)	S37 (1.62)
KI1	S3 (1.43)	-	S20 (4.07)	S29 (5.63)	S38 (1.25)
KI2	S4 (1.43)	S12 (1.43)	S21 (4.07)	S30 (5.63)	S39 (1.25)
KI3	S5 (0.94)	S13 (0.94)	S22 (2.74)	S31 (7.72)	S40 (1.71)
Ms1	S6 (1.80)	S14 (1.80)	S23 (5.11)	S32 (7.06)	S41 (1.57)
Ms2	S7 (1.80)	S15 (1.80)	S24 (5.11)	S33 (7.06)	S42 (1.57)
Pt1	S8 (1.72)	S16 (1.72)	S25 (4.89)	S34 (6.76)	S43 (1.50)
Cx1	S9 (1.83)	S17 (1.83)	S26 (5.21)	S35 (7.19)	S44 (1.60)

Table 1. LCA scenario frame (in brackets, application rate in dry matter ton/hectare)

<sup>2</sup> SS = sewage sludge

Due to the high amount of scenarios to analyse, some simplifications were made to the scenarios construction. Thus, each type of sludge is spread with the same tractor and spreader regardless of the cropping systems. Table 2 shows tractor and spreader characteristics.

Concerned scenarios	Pair	Tractor characteristics			Spreader characteristics		
		Engine power (kW)	Weight (kg)	Life time (h)	Capacity	Weight (kg)	Life time (h)
S1 to S9	P1	100	6880	7200	15 m <sup>3</sup> – precision splash plate	9250	2700
S10 to S17	P2	130	6650	7200	15 m <sup>3</sup> – 5 m injector, 11 spring tines	10836	2700
S18 to S26	P3	100	6880	7200	8,4 ton	4730	2000
S27 to S35	P4	100	6880	7200	6,8 ton	4730	2000
S36 to S44	P5	80	5790	7200	9,6 ton	4162	2000

Table 2: Tractor and spreader characteristics of each pair

Solid and composted sludges are transported by 16 ton lorry from the storage place after treatment (mainly at the waste water treatment plant) to an intermediate storage (distance of 35 km) and then by tractor and spreader to the field (distance of 2 km). Pelleted sludge is transported by 28 ton lorry from the storage place after treatment to an intermediate storage (distance of 100 km) and then by tractor and spreader to the field (distance of 2 km). Liquid sludge is directly transported by tractor and slurry tanker from the storage place after treatment to the field (distance of 4 km).

Some assumptions were made for the study. The first one is that the fertilisation plan is respected. The second assumption is that the material used is a standard well-maintained material. The last one is that there is no interruption during the spreading operations.

Some allocation rules were also established for the study. The tractor, the loader, the spreader and the shed are not only used for the spreading operations. This means that we need to allocate the materials and the shed in regard with the studied system and other operations requiring their use. The allocation rules for each material are established in proportion to the number of hours spent during the spreading operation. The allocation of the shed is based on the surface needed for each material in proportion to the hours spent during the spreading.

## Life Cycle Inventory

The life cycle inventory (LCI) consists of quantifying all the input and output data involved in the system. Data quantification is achieved according to the reference flow shown in Table 1.

### General data

Data concerning lorry transport operation, agricultural machinery, shed and fuel production come from Ecoinvent database v2.0. A specific process is created for slurry tanker with injection devices, as this process does not exist in Ecoinvent database. Emission calculation for tractor and loader fuel combustion and agricultural machinery tyre abrasion are based on Ecoinvent report n°15a (Nemecek, Kägi, 2007). A repair factor is applied to take the maintenance and repair of agricultural machinery into account. This repair factor is 0.21 for slurry tanker, 0.45 for injector and associated PVC, 0.34 for organic spreader and 0.2 for tractor (Nemecek, Kägi, 2007). LCA study is conducted with Simapro v7.1.8 software.

As we aim to assess nitrogenous emissions according to spreader technological performances, a specific method was built to inventory these emissions and link them with spreader technological characteristics. Likewise, realistic fuel consumption during the spreading operation phases (loading/filling up, transport, spreading) is assessed based on field experiments.

### **Experiments set-up to assess fuel consumption by tractors**

As specified in Lacour et al. (2010), long term monitoring equipments were installed on tractors in five agricultural equipment cooperatives in France. Each of them has to carry out spreading operations that could differ not only in kind of sludge, but also in machinery characteristics. Tractor velocity, fuel consumption and engine speed, as well as number of tanks and kind of sludge, are the typical parameters being recorded. During a whole year, data are collected representing 2000 hours of agricultural work and about 1000 hours of spreading operations.

The work is analysed through the comprehensive "tank unit". A tank unit is divided into four phases: filling up/loading of the spreader, full loaded transport to the field, spreading, and transport empty back. Then, average mission profiles are deduced from recorded data and fuel consumption in litres per hour bringing to light for each spreading operation phase.

Fuel consumption and tractor velocity data used for each scenario are shown in Table 3.

Concerned scenarios	Pair of spreading machine and sewage sludge	Filling up	Loading	Full transport	Empty transport	Spreading
S1 to S9	Slurry tanker – splash plate – liquid SS	<b>11 l/h</b> 0 km/h	nc <sup>3</sup>	<b>18 l/h</b> 16 km/h	<b>15 l/h</b> 20 km/h	<b>15 l/h</b> <sup>4</sup> 3-6 km/h
S10 to S17	Slurry tanker – injector – liquid SS	<b>11 l/h</b> 0 km/h	nc	<b>18 l/h</b> 16 km/h	<b>15 l/h</b> 20 km/h	<b>20 l/h</b> <sup>5</sup> 12-25 km/h
S18 to S26	Organic spreader – vertical moving rotors – solid SS	nc	<b>15 l/h</b> 0 km/h	<b>16.5 l/h</b> 16.5 km/h	<b>14.5 l/h</b> 23 km/h	<b>20 l/h</b> 8 km/h
S27 to S35	Organic spreader – vertical moving rotors – compost SS	nc	<b>15 l/h</b> 0 km/h	<b>16.5 l/h</b> 16.5 km/h	<b>14.5 l/h</b> 23 km/h	<b>18 l/h</b> 8 km/h
S36 to S44	Organic spreader – discs – pelleted SS	nc	<b>15 l/h</b> 0 km/h	<b>16.5 l/h</b> 16.5 km/h	<b>14.5 l/h</b> 23 km/h	<b>18 l/h</b> 8 km/h

Table 3: **Fuel consumption (l/h)** and *tractor velocity (km/h)* used for each scenario

Fuel consumption and tractor velocity during the sludge incorporation is assessed to be respectively 11 l/h and 16 km/h for transport phase and 12 l/ha for incorporation regardless of the scenario (Minette, 2009).

### **Method to assess nitrogenous emissions, according to the environmental performances of spreaders**

This method is developed through a three step procedure: (i) assessing spreader technological performance indicators, (ii) identifying the main indicators having an impact on nitrogenous emissions, (iii) simulating nitrogenous emissions through agronomic models or specific equations involving these indicators.

Forty-two technological indicators were developed to assess nine field performances representative of field work expectations, such as spatial distribution homogeneity, application rate accuracy, energetic performances, good sludge projection, good fractioning, good incorporation or soil deposit, poor soil compaction, small rut surface, and poor natural resource consumption for spreader manufacturing (Pradel et al., 2010; Rousselet et al., 2010). Among these indicators, only seven have a direct influence on nitrogenous emissions. For three of them (spatial distribution, application rate and soil compaction), biophysical models such as STICS (Brisson, Mary, 1998) or Compsol (O'Sullivan et al., 1999) are used

<sup>3</sup> nc = not concerned

<sup>4</sup> We considered that there is no change in fuel consumption when tractor velocity varies from 3 to 6 km/h.

<sup>5</sup> We considered that, as injection is more energy consuming, 5 l/h are added to the 15 l/h measured for slurry tanker using a splash plate device.

(Pacaud et al., 2010), taking real performances and characteristics from test bench and spreading simulator (Piron et al., 2009) into account.

For the remaining indicators (fractioning, projection, incorporation/soil deposit), specific equations were developed to link the nitrogenous emissions to the corresponding technological indicators. We assume that a good value (10) for an indicator does not generate more nitrogenous emissions than those in the standard (especially IPCC standard). On the contrary, a bad value (1 or 0) generates a high rate of concerned emission. Appendix A explains the corresponding emissions and the equation construction for fractioning, incorporation/soil deposit and projection.

As a result, for each scenario, we obtain for each scenario an emission value in kg/dry matter ton of spread sludge for ammonia volatilisation, nitrous oxide emission and nitrate leaching (Table 4).

Cropping systems	Nitrogenous emission in kg/dry matter ton of spread sludge				
	Slurry tanker – splash plate – liquid SS <sup>6</sup>	Slurry tanker – injector – liquid SS	Organic spreader – vertical moving rotors – solid SS	Organic spreader – vertical moving rotors – compost SS	Organic spreader – discs – pelleted SS
Mt1	<b>12.1</b> , 0.0, <u>32.9</u>	<b>1.3</b> , 1.4, <u>6.9</u>	<b>1.6</b> , 0.0, <u>1.3</u>	<b>1.0</b> , 0.0, <u>22.5</u>	<b>2.9</b> , 0.0, <u>26.2</u>
Mt2	<b>17.5</b> , 0.0, <u>20.6</u>	<b>3.3</b> , 1.4, <u>-6.2</u>	<b>2.7</b> , 0.0, <u>0.0</u>	<b>2.0</b> , 0.0, <u>22.2</u>	<b>6.4</b> , 0.0, <u>19.2</u>
KI1	<b>5.3</b> , 0.5, <u>20.7</u>	-	<b>0.3</b> , 1.2, <u>-0.7</u>	<b>0.7</b> , 0.1, <u>21.8</u>	<b>0.0</b> , 0.3, <u>18.8</u>
KI2	<b>9.0</b> , 0.6, <u>23.6</u>	<b>0.8</b> , 1.7, <u>-1.2</u>	<b>1.1</b> , 1.3, <u>-1.3</u>	<b>1.0</b> , 0.2, <u>21.3</u>	<b>2.0</b> , 0.3, <u>17.7</u>
KI3	<b>5.3</b> , 1.3, <u>25.6</u>	<b>0.0</b> , 2.0, <u>2.1</u>	<b>0.3</b> , 1.8, <u>-1.2</u>	<b>0.5</b> , 0.2, <u>21.8</u>	<b>0.0</b> , 0.4, <u>18.8</u>
Ms1	<b>12.1</b> , 0.0, <u>33.1</u>	<b>4.7</b> , 1.4, <u>7.0</u>	<b>4.3</b> , 0.0, <u>1.0</u>	<b>3.1</b> , 0.0, <u>22.2</u>	<b>13.6</b> , 0.0, <u>19.6</u>
Ms2	<b>22.1</b> , 0.0, <u>31.9</u>	<b>7.4</b> , 1.4, <u>5.7</u>	<b>4.3</b> , 0.0, <u>1.4</u>	<b>3.1</b> , 0.0, <u>22.4</u>	<b>13.6</b> , 0.0, <u>21.3</u>
Pt1	<b>13.7</b> , 16.4, <u>68.5</u>	<b>6.3</b> , 10.0, <u>52.6</u>	<b>2.9</b> , 4.5, <u>1.0</u>	<b>2.7</b> , 3.0, <u>20.8</u>	<b>9.1</b> , 14.8, <u>18.9</u>
Cx1	<b>8.8</b> , 0.0, <u>60.3</u>	<b>2.6</b> , 1.4, <u>35.5</u>	<b>1.6</b> , 0.0, <u>1.3</u>	<b>1.3</b> , 0.0, <u>7.6</u>	<b>4.5</b> , 0.0, <u>31.3</u>

Table 4: **Ammonia**, *nitrous oxide* and *nitrate* emissions obtained after simulations and specific equations

## Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) converts each quantified inventory flow into corresponding environmental impact categories through a characterisation factor.

Different methodologies can be used to assess environmental impacts. We chose two methods: Eco-indicator 99, developed by PRé Consultants (Goedkoop, Spriensma, 2001) and the CML baseline 2 method, developed by the Institute of Environmental Sciences of Leiden in Netherlands (Guinée et al., 2001).

The Eco-indicator 99 method is an endpoint oriented method. It is well documented and regularly used for LCA studies. By an aggregation procedure, this method produces a single score, also called Ecoindicator value, representing the total environmental burden for each system under investigation.

The CML method is a midpoint oriented method and is well adapted to agricultural LCA (Basset-Mens, Van Der Werf, 2005), establishing a difference between the acidification and eutrophication impact categories in opposition to other methods. The following impacts were considered: abiotic depletion (AD), global warming (GWP100), ozone layer depletion (ODP), human toxicity (HT), aquatic toxicity (fresh water (FWAE) and marine (MAE)), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (AP) and eutrophication (EP).

## Interpretation

LCA interpretation consists of providing an understandable, complete and consistent presentation of LCA results in accordance with the goal and scope definition of the study.

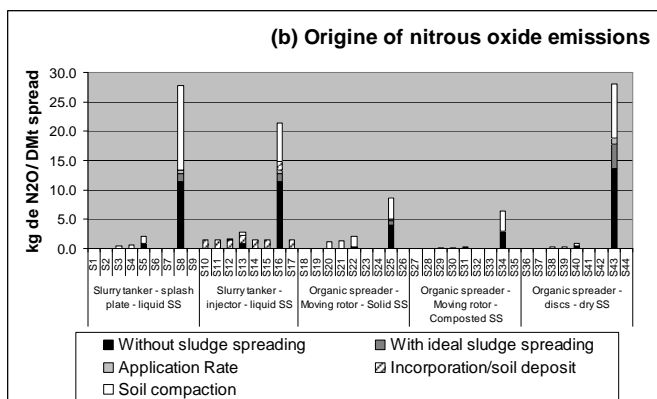
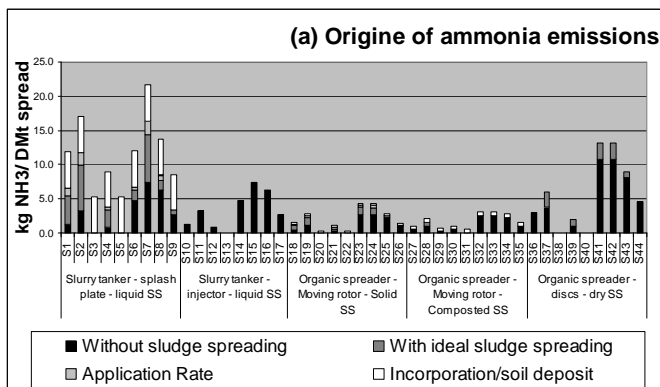
<sup>6</sup> SS = sewage sludge

## Results and discussion

### Nitrogenous emission origins according to spreader technological performances

According to the method proposed by Pacaud et al. (2010) and the equations proposed in Appendix A, we calculated the nitrogenous emissions produced by the different studied spreading operations (Figure 2).

Results show that spreading liquid SS<sup>7</sup> with a splash plate produces more ammonia emissions than the other spreading techniques. While ammonia emissions are not linked with the spreader performances for other application techniques, the soil deposit and, to a lesser extent, the application rate measured for the slurry tanker equipped with a splash plate have



an effect on ammonia emissions for liquid SS spreading (Figure 2a). In addition, using an injection technique reduces ammonia emission in comparison with splash plate technique.

Nitrous oxide emissions are only produced in a pedoclimatic condition, where denitrification potential seems to be high and sensitive to soil compaction (Figure 2b).

Finally, nitrate emissions are barely linked with spreader technological performances and depend mostly on soil and climatic conditions (Figure 2c).

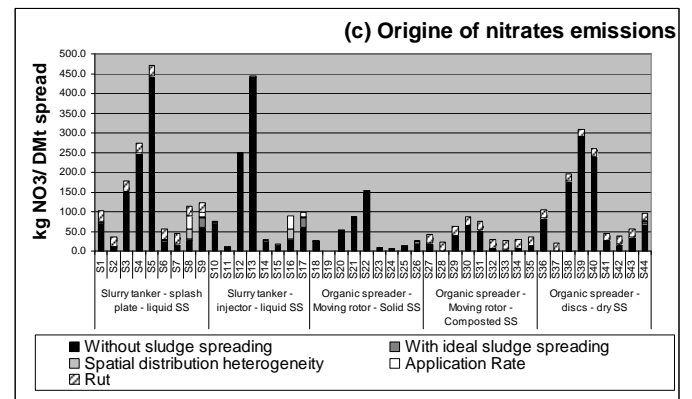


Figure 2: Nitrogenous emissions according to spreader technological performances

### Spreading scenario environmental impact analysis

As there are numerous LCA results, we put an emphasis on two main aspects: the differences between spreading machines and the influence of pedoclimatic conditions.

#### *Do environmental impacts present significant differences between the spreading machines?*

Figure 3 presents the LCA results for spreading operation involving two of the five pairs of "sewage sludge-spreading machine": (a) solid sewage sludge spread using an organic spreader with vertical rotors and (b) liquid sewage sludge injection. Mean and standard deviation values result from the impacts related to the different pedoclimatic conditions. Only spreading phases representing more than 5% for each impact are shown.

Nitrogenous emissions mainly impact on eutrophication (almost 99%), acidification (between 75 to 95%) regardless of the spreading scenarios. Nitrogenous emissions contribute to around 35% of the GWP100 impact categories for all the scenarios, except for injection as it represents 90%.

<sup>7</sup> SS = sewage sludge

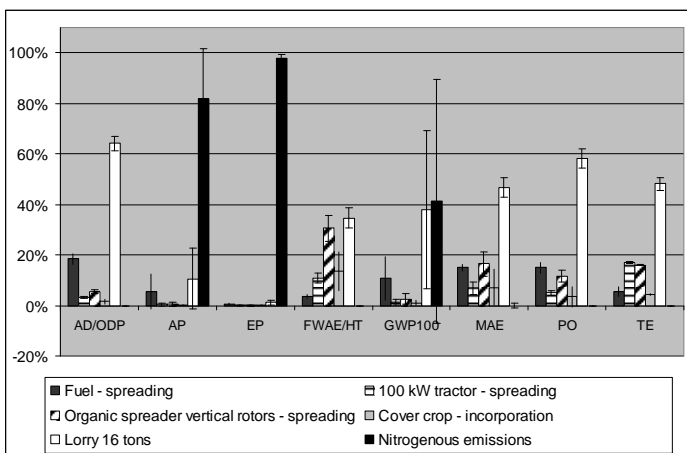


Solid and composted sludge transport from the storage place after treatment to an intermediate storage by a 16 ton lorry on 35 km is the most impacting element for almost all categories. However, sludge transport and organic spreader production equally impact on fresh water aquatic and human toxicity categories. In the same manner, transport equally impacts with nitrogenous emissions on GWP100.

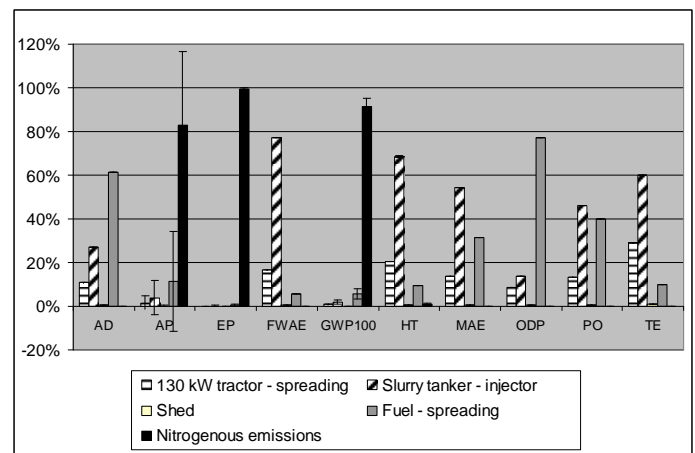
Pelleted sludge transport from the storage place after treatment to an intermediate storage by a 28 ton lorry on 100 km equally impacts on each category (except AP and EP). Spreader and tractor production and fuel emissions (during both production and combustion) have the same impact contribution (results not shown). As a conclusion, pelleted sludge transport (89% of dry matter per ton) on great distances with a high volume lorry (28 tons) has fewer impacts than solid and composted sludge transport (respectively 64 and 33% of dry matter par ton) on average distances with a low volume lorry (16 tons).

Without sludge transport by lorry, agricultural material, spreader and tractor manufacturing affects most of the toxicity impact categories and, to a lesser extent, abiotic depletion. Fuel production and combustion in the tractor engine mainly impact on ozone layer depletion and abiotic depletion. Photochemical oxidation is equally produced by spreader manufacturing and fuel production, as well as by combustion in the tractor engine. Cover crop transport and use for incorporation has a low impact for all sludge spreading scenarios.

We also observed a high variability in GWP100 and acidification LCA results caused by a high variability in nitrous oxide and ammonia emissions, respectively. This high variability is strongly connected to the pedoclimatic conditions as reported by Pacaud et al. (2010) and illustrated in the previous section.



(a) Organic spreader – vertical rotors – solid SS



(b) Slurry tanker – injection – liquid SS

Figure 3: Environmental impacts of sewage sludge spreading for two technologies using mean and standard deviation values from the impacts of the nine pedoclimatic conditions (CML 2 baseline 2000 V2.04 / characterisation)

**Do the pedoclimatic conditions have an influence on the environmental impact of spreading scenarios?**

Figure 4 represents a comparative LCA result between liquid sewage sludge spread with a splash plate and with injectors using Ecoindicator 99 method. Unlike Figure 3, which presents the mean and standard deviation values from the impacts of the nine pedoclimatic conditions, Figure 4 presents LCA results for each pedoclimatic conditions using Ecoindicator single score.

As explained by Goedkoop and Spriensma (2001) and illustrated by Bentrup et al. (2001), these single scores are dimensionless and then can be summed up to present the total environmental burden of the studied scenarios.

Generally, single scores are more important for liquid sludge spreading using splash plate regardless of the pedoclimatic conditions, as we considered an incorporation with cover crop while this step is not taken into account in liquid sludge spreading through injection.

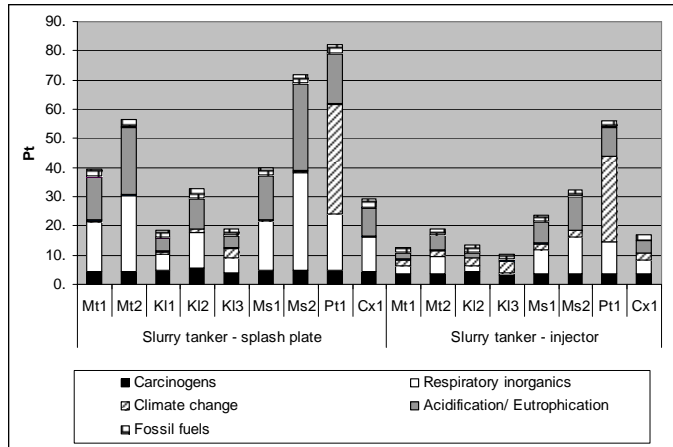


Figure 4: Comparison of liquid sewage sludge spreading using slurry tanker equipped with splash plate or injectors (Eco-indicator 99 (E) V2.06 / single score)

So, we observe that spreading liquid sewage sludge, whether using splash plate or injectors, is more impacting in Poitou Charentes pedoclimatic context than in other sites. This can be explained by the high denitrification potential of the local pedoclimatic conditions affecting climate change. According to the pedoclimatic conditions, spreading sludge using injector devices reduces impacts between 10 and 30 single scores (Pt) compared with spreading using splash plate devices.

## Conclusion

Our LCA study highlights that it is possible to accurately discriminate environmental performances integrating spreaders technological performances for several spreading operations. We also show the importance of the spreading operation phases (loading, transport, spreading) in terms of environmental impacts leading to a better understanding of the spreading operations and to a possible reduction of the main identified environmental impacts.

The proposed method links nitrogenous emissions to the spreader technological performances so that the main spreader technological characteristics can be improved. This step is included within a bigger approach on the spreaders ecodesign.

However, LCA results can not be generalised to all the spreading operations because of both, the high variability in nitrogenous emissions strongly linked to the spreader performances and the specific conditions and assumptions established for scenarios construction, especially regarding sludge transport by lorry.

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## Appendix A: Equation construction used to link nitrogenous emissions and spreader technological performances

### Emissions based on spreader fractioning performances

Fractioning mainly causes nitrous oxide emissions as incorporating big mass of non fractioned sludges generates anaerobic hot spots and is favourable to denitrification process. We assume that for a bad indicator value of "1", nitrous oxide emission factor is 1.58% (resulting from a mean value of literature denitrification potential), whereas for a good indicator value of "10", nitrous oxide emission factor is 1.25% according to IPCC.

Emission factor  $EF_{N_2O_f}$  based on fractioning indicator is calculated according to Equation 1.

$$\text{Equation 1} \quad EF_{N_2O_f} = 1.57 \times (0.37 - 0.037 I_{F_2}) \times [N_t] / 100$$

where  $I_{F_2}$  is the fractioning indicator representing spreader fractioning performance (between 1 and 10), 1,57 is the conversion mass of N-N<sub>2</sub>O in N<sub>2</sub>O and  $[N_t]$  the concentration in total nitrogen of the sludge (in kg/dry matter ton).

### Emissions based on spreader projection performances

Sludge projection mainly generates ammonia volatilisation. Emission factor  $EF_{NH_3p}$  based on the spreader projection performances is calculated according to Equation 2.

$$\text{Equation 2} \quad EF_{NH_3p} = 1.21 \times [N - NH_4] \times (100 - (I_{P_2} \times I_{P_3})) / 1000$$

where  $I_{P_2}$  is the diameter drop indicator and  $I_{P_3}$  is the projection length indicator both representing spreader projection performances (between 0 and 10), 1.21 is the conversion mass of N-NH<sub>3</sub> in NH<sub>3</sub> and  $[N-NH_4]$  the concentration in total ammoniacal nitrogen of the sludge (in kg/dry matter ton).

### Emissions based on spreader incorporation/soil deposit performances

Sludge incorporation generates nitrous oxide emission while soil deposit generates ammonia volatilisation. We propose two equations (respectively Equation 3 and Equation 4) to calculate these emissions based on spreader incorporation/soil deposit performances.

$$\text{Equation 3} \quad EF_{N_2O_i} = 1.57 \times 0.0125 \times [N_t] \times (Prof / 10)$$

where  $Prof$  is the incorporation depth (in cm – between 0 and 10), 1,57 is the conversion mass of N-N<sub>2</sub>O in N<sub>2</sub>O, 0.0125 the IPCC N<sub>2</sub>O emission factor and  $[N_t]$  the concentration in total nitrogen of the sludge (in kg/dry matter ton).

$$\text{Equation 4} \quad EF_{NH_3sd} = 1.21 \times [N - NH_4] \times k$$

where 1.21 is the conversion mass of N-NH<sub>3</sub> in NH<sub>3</sub>,  $[N-NH_4]$  the concentration in total ammoniacal nitrogen of the sludge (in kg/dry matter ton) and  $k$  a coefficient based on the incorporation delay and the type of spreading (table 5).

Sludge and spreader characteristics		Immediate incorporation	Incorporation 24 hours after spreading	Without incorporation or incorporation later than 24 hours after spreading
Liquid	Splash plate		$k = 0,5$	$k = 0,6$
	Trailing hoses		$k = 0,35 - 0,01 * I_{E_3}$ Where $I_{E_3}$ is the area covered by sludge (scored 0 to 10)	$k = 0,40 - 0,01 * I_{E_3}$
	Injectors	$k = (0,35 - 0,01 * I_{E_1}) * (1 - 0,1 * Prof)$ Where $I_{E_1}$ represent the non incorporated area (scored 0 to 10)		
Solid or pasty	Organic spreader		$k=0,25$	$k=0,30$
Pelleted	Organic spreader		$k = 0$	$k=0$

Table 5: Calculation of  $k$  coefficient for Equation 4