Life-cycle assessment as a method for environmental assessment and its application to agricultural machinery

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1. Introduction

Pushed by regulations which, wherever in the world, but especially in Europe, require more and more environment-friendly agricultural practices, farm machinery manufacturers have been consequently incited to design more environment-friendly machines. However, relevantly measuring the environmental performance of agricultural machinery is not that easy. Standards have been written for years to assess the properties of agricultural machinery, in order to better monitor their performances. For instance, for manure spreaders, various standards for checking environmental performances are available such as NF EN 13080 for manure spreaders [*1*], NF EN 13406[*2*] for slurry spreaders, or NF EN 13739 [*3*] which deals with solid fertilizer spreaders, but they do focus on two properties only, ie the longitudinal and transversal spreading of the fertilizing material. This rises up two types of issues: first it does not cover all the possible impacts due to spreaders; for instance, the fuel consumption or the consumption of iron to build up the machinery are not taken into account. Second, providing indicators about the good - or bad - display of fertilizing material does not account on the real environmental impact: how much would a bad display lead to a high impact towards ecosystems or human health? Moreover, these standards suppose that the spreading homogeneity be the key operating factor of the equipment dedicated to spread pesticide. This is dangerous as it prevent other innovative technologies to be compliant with the standard. Let's take an example with pesticide sprayers, for which environmental performances are measured through the ISO 16 119 series [*4*]. In that case, the environmental performances of a weeder applying herbicides would be assessed via the stability performances of horizontal boom sprayers. This means that a highly innovative system such as electrical weeding could not be assessed using this standard and therefore would lose commercial credit.

As a consequence, although standards based on technical performances assessment are satisfactory, at first order, for promoting agricultural machinery improvement, they are not enough to encompass the various environment impacts a farm equipment can cause. Such a generic methodology that would help agricultural equipment designers to systematically explore the various potential impacts of any farm machinery is still expected and bibliography show very little production in this area: a bibliographic study carried out from 2000 up to now and crossing [“environmental” and “impact” and (“agricultural” or “farm”) and (“equipment” or “machinery”)] resulted in only 150 papers, of which only a dozen could be relayed to the assessment of the environmental performances of agricultural machineries! The other ones were dealing with comparison of agricultural practices (ie organic vs conventional, tillage vs no-tillage, etc).

The aim of this paper is to introduce a introduce a methodology which may comply to these requirements. This methodology, ie Life Cycle Assessment or LCA, has been used for years for manufactured products and could be used for agricultural equipments, in order to thoroughly assess their environmental performances.

This paper will first introduce LCA and then will describe how it was used for assessing the environmental performance of spreaders, with a special emphasis on the link between LCA and

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technological characteristics. Finally, we will advices about how to apply this method to farm machinery.

2. Principles and methodology of LCA

2.1 History and principles

First product-oriented environmental assessments were conducted in the US in the 1970s. They mainly focused on assessing the consumption of resources and energy and waste [*5*]. After these first attempts, named Resource and Environmental Profile Analysis, the method underwent significant development efforts and methodological harmonization under the auspices of three organizations: the SETAC (Society of Toxicology and Chemistry of the Environment), the ISO (international Standardization Organization) and UNEP (United Nations environment)[*6*]. Today, LCA can be considered as one of the main assessment tools for product development under environmental policy [*7*].

LCA has been standardized through the ISO 14040 series [*8*]. This standard defines LCA as the "compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system throughout its life cycle", ie extraction of raw materials to waste. The objectives of a LCA can be many, but Guinée et al [*6*] propose to restrict "to compile and evaluate the environmental consequences of different options for a fulfilling some function." The strengths of LCA as a framework for evaluating the environmental performances of a product are the following ones:

- First, LCA covers the whole “life” of a product, including also the phases necessary to provide the raw materials necessary for the product building; this prevent from impact transfers from one lifecycle stage to another one;

- Second LCA covers a wide range of impacts, therefore preventing from transfers from one to another impact category to another (ex: ecotoxicity reduction but GHG emission growth);

- Third, LCA is standardized and the framework must be thoroughly followed which offers good reproducibility of the results;

- Fourth, LCA deals with products described by their functions (for instance: protecting 1 ha of a 3000 stock/ha vineyard from mildew), and not by their nature; therefore two technologies having the same aim ie the same function (eg weeding) but not using the same technology (eg herbicide spraying, thermal weeding of electrical weeding) can be compared;

The LCA methodology as described by ISO 14040 requires four steps (**Figure 1**):

- Step 1: scope and goal of the study, functional unit.
- Step 2: Inventory of materials and energy flows associated with the stages of the life cycle reported to the functional unit used
- Step 3: Assessment of potential impacts from energy and material flows identified
- Step 4: Interpretation of results against targets selected

In the following these steps are thoroughly described.

2.2 LCA step 1: Goal and scope

In this step, which is essential to the quality of the study, the objectives of the study and the studied system are defined. The application of the study and the audience, the results will be communicated to, must be provided here. The scope is defined at step 1: it must include several elements such as the functions of the studied system and more specifically the function under study, and its measurement unit, called the functional unit. The definition of the functional unit is fundamental because the assessment is based on the product functions and not the products themselves. For example, two types of bulbs, incandescent and fluorescent are not directly compared on the basis of their nature (ie 1 bulb), but on the basis of their function, ie lighting at a certain amount of lumens and a certain time (eg providing 600 lumens for 6000 hours). All the impacts will be computed with regard to this unit. However, this functional unit has to be precise enough to be relevant: it would be irrelevant to compare ski boots with flip-flops because their main function, although similar (protecting the foot) is different.

The system boundaries must also be described at this stage: they set the limits of the system which is necessary to provide the studied function. It is often represented as a process tree, which can rapidly be huge if raw material extraction is taken into account; to avoid it the standard 14044 indicates cut-off criteria which define whether or not to include a process, on the basis of their contribution to mass, energy or environmental impact. Last, the allocation rules are defined in this first step. Allocation is necessary whenever a single process produces several products. For instance, a cow will provide milk, meat, manure and slurry. Which part of environmental impact is to be supported by each of these "productions"? This depends on the allocation choices which are decided by the LCA practitioner and which can dramatically change the result of LCA. For agricultural machinery this would be the case of a machine providing 2 independent functions at a time. So this step is highly controversial [*9*] and should be avoided whenever possible. Guidelines are given in the standard 14044 as well as by several studies.

2.3 Life cycle inventory

On the basis of the tree process built in step 1, the inventory phase is to systematically identify any consumption of raw materials and energy (inputs) and all environmental emissions (outputs). The development of inventory may be based on measurements, models and / or statements of expert. Inventory databases have been established; the directory of available databases is regularly updated by UNEP. Especially noteworthy, the Ecoinvent database contains a large number of data from the sectors of energy and transport. However, it is very general with regard to agricultural practices and could not be used for comparing two agricultural equipments: data availability for machine building would not be a problem, but it certainly would for processes related to machine use (how much N_2O, CO_2, etc would be released when using such or such spreader, for instance, is not trivial to say). This step is the one which requires most efforts. In the case of agricultural machinery, most difficult task is to make the inventory of the stage of use. Whereas the accounting of consumptions (of energy, and other inputs) may be rather correctly and sometimes easily done, the real challenge is to compute the emissions of various pollutants, as well as the compartments were they are emitted to. This is to be carried out by coupling trial results and models, as will be shown in the example below.

2.4 The environmental impact assessment

LCA aims at covering all impacts affecting "areas of protection" (AoP) the society wants to preserve, more specifically (i) the ecosystems, (ii) the human health and (iii) natural resources. Adjustments are possible: some researchers made the difference between renewable and non-renewable resources, others add "man-made environment" Guinea et al. [2001]. All the flows listed at the inventory phase are translated into environmental impacts, first into "impact categories", called "mid-point impacts" (as GHG emission, eutrophication etc), second into "damages to the AoP, called "end-point impacts". During the "characterization phase", LCA must (i) list the selected models (for translation of emissions into mid-point impacts) and impact categories, (ii) classify each flow listed in the inventory phase in the appropriate impact categories, (iii) calculate the equivalence of each elementary emission flow into units of the impact category.

Several models have been developed to translate the elementary emission flows into mid-point impact units. These models take into account the inherent properties of substances but not the characteristics of the environment in which they are emitted, which is considered standard or generic [*10*]. These models include different stages of the causal chain from the emission of a substance in the environment to its impact on areas of protection. For instance, ammonia emission can cause air acidification, which leads to acid rain which, in turn, acidifies lakes causing the death of aquatic organisms and resulting in a biodiversity loss. For each impact category, the function which transforms the emitted flow into an impact is called the characterization factor. For example, in the CML method, methane has a greenhouse effect as high as 23 times CO_2's one. Flows are summed over all phases of the product life cycle and the potential impacts are calculated using a linear relationship:

$$PI(j) = f_{j,i} \times Q_i$$

with PI (j) the potential impact of category j, fj,i is the characterization factor of each substance i in the impact category j, Qi and the amount of substance consumed or emitted in the studied life cycle.

Then, other models are used to turn these mid-point impacts into damages to the AoP. Uncertainty grows along the causal chain, which has led some characterization methods, such as CML [*6*] and EDIP [*5*] to stick to the early stages of the causal chain (impact endpoint) to provide an assessment. There is a trade-off between uncertainty and relevance: the further we go in the chain, the more relevant but the more uncertain. At the end of this step, the results can be "normalized", ie related to baseline values. This allows us to compare the results of each impact category on a common basis. The normalization reference values are generally the value of the impact at the level of a country, a continent or the world for a year. For each impact category, normalization makes it possible to compare the contributions of the studied product to the global impact on the scale of a country, a continent or the world on a year [*11*].

2.5 Interpretation

Figure 1 shows that the interpretation is not only the final interpretation and discussion of the results of the assessment, but it should occur at every LCA stages to clearly state all assumptions and choices in order to provide all the elements for judging the result significance.

3. Application to agricultural equipment – the ECODEFI project

3.1 General frame

The aim of this chapter is to show how LCA has been used in practice for evaluating the performances of spreaders. This study has been carried out through a project subsidized by the ministry of Research in 2006-2009. This study has given birth to one PhD study [*12*], 2 publications [*13-14*] and to a simplified LCA tool (ACV 3E) for making LCA of spreading operations.

Application techniques are currently studied from a technological perspective on distribution (eg [*15*]), application rate (eg [*16*]), soil compaction (eg [*17*]) but very few papers evaluate the technological performances of application techniques. Recently, Dinuccio et Balsari [*18*] evaluated the ammonia emission based on spreader testing but did not go until final impact. As said above, the evaluation of the environmental performance of agricultural spreaders is today limited to the measurement of the transverse and longitudinal distributions of spread fertilizer (NF EN 13080 standard for manure spreaders and NF EN 13406 for slurry spreaders), but with no direct links to environmental impacts.

The aim of the ECODEFI project was to develop a new environmental assessment method on the basis of LCA. The functional unit is therefore “spreading one ton of manure”. LCA is used twice in our methodology:

- First, as an exhaustive but rather rough analysis of the studied process (ie slurry spreading) in order to point out which processes of the process tree are the most impacting ones;

- Second, more finely with the aim to compare the various equipments, by focusing on the causal chains related to most impacting processes. In this second phase, we may have to carry out experimental studies in order to refine the causal chains. One difficulty is to account for the variability of emissions due to climate and soil conditions, which add uncertainty to the LCA results.

Four application techniques were considered i) band spreading with trailing hoses (BAND) which is chosen as the reference application technique, ii) broadcast spreading with a splash plate device (BROAD), iii) surface application followed by a shallow incorporation of the slurry with a harrow (HARR) and iv) direct injection (INJ). The BAND was chosen as the reference technique. Application techniques were compared regarding the field application of 100 kg of nitrogen from slurry over 1 ha, which is the functional unit. The processes included in the study are shown in **Figure 2**.

Whereas the transportation phase was included in the system, the storage phase was excluded since it was the same for the four techniques.

The first rough LCA study allowed us to conclude that the main impact categories were acidification, eutrophication and climate change [*13*]. The present study was thus limited to these three categories.

3.2 LCA of the 4 spreading technologies

3.2.1 Sources of data

Due to the importance of N emissions, a particular emphasis was made on the estimation of N losses and a generic method was developed to explore their routes. The N losses estimates have been calculated in successive steps:

1. We gathered experimental results on NH_3 and N_2O direct emissions of different application techniques through a literature review, in order to calculate relative loss factors ki,j (where i is the emission, either N_2O or NH_3 and j is the technology) compared with the reference technique (ie BAND);

2. Absolute NH_3 and N_2O direct emissions for the band spreading technique were assessed in a given situation. For NH_3, we considered that the TAN amount for 15%N in the slurry. NH_3 and N_2O emissions for the other techniques were obtained by multiplying N losses for band spreading in the given situation with the relative loss factors calculated in step 1 ;

3. Indirect N_2O emissions were estimated with the IPCC emission factors [*19*].

4. Nitrate leaching was defined as a function of NH_3 and N_2O direct emissions. A leaching factor $C_{leached}$ was determined from the bibliography. It was estimated for one given situation and was considered the same for any technique.

The figures relative to equipment running were the following ones (Table 1). The slurry is transported with the same tractor used for the slurry application in a 10 m^3 tanker filled at 90 % of its capacity. The distance between the slurry storage location and the field was set to 4 km. Data relative to the production of tractors, slurry tanker and application device were taken from Ecoinvent LCA database (v 2.0). Emissions due to fuel consumption were derived from tractor tests realized by FAT Tanikon.

As said above, variability of the N emission may be high due to the variability of soil and climatic conditions. Based on the literature review, we have defined the range of variability for each ki,j, after the extreme highest and lowest values have been removed. This range can at first order represent various soil and weather conditions.

3.2.2 Results

This first study ends up with a comparison of the emission factors for the 4 technologies, the band spreader being the reference one (ie k = 1) (**Figure 3**). For NO3, NH3 losses were always higher with a broadly spread slurry than with a banded slurry except for one case. Similarly, except for one case, volatilization with injection, and to a lesser extent harrowing, was always less compared to that of band spreading. Nevertheless, both techniques showed an important variability, partly explained by the difference in the depths of slurry placement between the experiments.

For N2O, the effect of injection showed a huge dispersion, which is related to a controversy: some authors found that injection had no effect on N_2O emissions, while others found the contrary. Besides, N_20fluxes measurements are known to have a high spatial and temporal variability with typical coefficient of variation exceeding 100 % . It is therefore difficult to conclude.

The various N emissions are therefore computed from the above results and the knowledge of $C_{leached}$. They are given in **Table 2**.

When emissions other than nitrogenous ones are added and mid-term impacts are computed, we get the results shown in **Figure 4**. From this figure, it is possible to carry out a robust environmental analysis of the four techniques despite the variability of the field emissions, caused by various conditions of soil, weather and slurry type in the papers. Injection and harrowing showed the best reduction of NH_3 volatilization, but this benefit was mitigated by increased N_2O emissions, which could be particularly important with injection. Harrowing therefore appeared as the best compromise, reducing NH_3 losses and offering less risk regarding GWP100.

To achieve a more refined comparison between the techniques, the use of process-based models and field measurements carried out in contrasted situations may prove useful. This will be shown in the next paragraph.

3.3 From LCA to the evaluation of technological characteristics [14]

In the preceding example, technologies were compared based on data from the bibliography. However, when one searches to assess the impact of a new technology on the environment, bibliographic data are no longer available. To make a link between application techniques performances and related nitrogen emissions in the field, it is therefore necessary to find and use models describing the phenomena occurring in the causal chain and to determine which technical parameters are to be measured to feed these models. Irstea (Montoldre) has therefore worked on the general frame to bridge the gap between the characteristics of the spreaders and the nitrogenous emissions they are responsible for.

3.3.1 Methodology

The methodology has been thoroughly described in ([*14*]). It consists in a 4-step method:

The first step deals with (1) identifying the biophysical models to be further used to estimate emissions and (2) to creating scenarios that will provide input data for the biophysical models; each scenario associates a cropping system and a spreading operation (spreading machine, sewage sludge, spreading period).

In the second step, we test some technological performances of the spreaders, ie spatial distribution and application rate efficiency, via a test bench. The outputs are used as input data of a “spreading simulator” to estimate the in-field spatial distribution and application rate performances. The effect of spreaders on soil compaction is assessed with the Compsoil model [*20*] based on the spreader technological characteristics. Therefore, at the end of this step, we have (i) a distribution of the application rate efficiency at the sub-field scale, (ii) the distribution and the bulk densities of compacted and non compacted areas.

In the third step, the nitrogenous emissions generated by each application rate class are estimated with biophysical models, ie STICS [*21*] and DEAC [*22*]. STICS will be also able to assess nitrogenous emissions in compacted and non compacted areas. This is done for an elementary area (1 m²).

Finally, the emission are estimated for a given scenario by multiplying the percentage of each class of bulk density / application rate (determined in step 2) by the emission rate calculated in step 3. This allows us to calculate the nitrogen losses at the field scale due to the spreader performances respectively on spatial distribution, application rate efficiency and soil compaction.

3.3.2 Application

Step 1. We have studied 45 scenarios, defined by a panel of experts, by crossing 9 sites (**Table 3**) with 5 application techniques (Table 4). One scenario, judged unrealistic, was removed.

Step 2. The “spreading pattern” (i.e. longitudinal and transversal distributions) of each spreader is determined using CEMOB test bench (Irstea, Montoldre). To estimate the sewage sludge distribution on a field, we combine this spreading pattern with the trajectory of the spreader thanks to a spreading simulator [*23*]. Three parameters are required for the software: (i) the spreading pattern, (ii) the field operational parameters (field shape and size, trajectory of the spreader), (iii) the spreader discharge rate characteristics.

Step 3. The compaction risk due to the spreader depends on the load applied on each wheel and on the contact area between the soil and each tire. The load is automatically measured on the CEMOB test bench. The contact area after measuring ARs, w_{ss} and w_{rs}, by the following equation:

$$A_{sc} = A_{rs}(0{,}375 + 0{,}625(\frac{w_{ss}}{w_{rs}})^2)$$

Where A_{sc} is the contact area in spreading condition, A_{rs} is the contact area on a rigid soil, w_{ss} is the width of the contact area on soft soil and w_{rs} is the width of the contact area on a rigid soil.

From the area determined by testing the machine (ie A_{sc} value), COMPSOIL calculates the stress distribution and propagation through the soil and estimates compaction from the stress according to soil characteristics, given by the scenarios. It provides: (i) the bulk density in and outside compacted areas, (ii) the proportion of compacted/not compacted area in %.

Step 4. Based on the 44 scenarios, inputs related to the cropping systems (climate, soils and practices) and the sewage sludge (chemical characteristics) were integrated into DEAC and STICS models to estimate annual total nitrogen losses following the sewage sludge spreading. For each site, a representative year was chosen so as to avoid extreme values. Simulations were then conducted for each scenario to obtained nitrogen losses regarding a wide range of application rates (from zero to double rate) and first soil layer bulk densities (from 0.8 to 1.7 g cm^{-3} of soil).

3.3.2 Results

The following tables show for the 44 scenarios the additional nitrogen flows, with regard to a 100% evenly distributed fertilizer with no soil compaction: **Figure 5** shows the influence of uneven distribution, and **Figure 6** shows the influence of soil compaction.

For each of the 44 scenarios, we have also compared the simulated emissions with the ones given by the IPCC factors classically used in LCA (Table 5). Big discrepancies are revealed. There are due to the fact that IPCC factors do not take into account neither weather and soil conditions, nor distribution parameters. It appears that nitrate emissions are dependent on soil/ weather conditions but not on spreader distribution patterns. On the contrary, ammonia volatilization care directly linked to the type of spreading operation. The same is true for nitrous oxide emissions, linked to the spreader weight as well as soil / weather conditions.

Having highlighted that the spreader performances and their effects on nitrogenous emissions strongly depend on the local environment leads us to conclude that when LCA is used for comparing technologies, these parameters should be taken into account: it is crucial to carry out LCAs using emission factors computed in a wide range of weather / soil situations in order to have the relevant impacts and being able to really compare technologies. This method can help spreader manufacturers in improving the technological performances of their spreader through ecodesign based on LCA.

4. Conclusion

LCA appears to be very appealing for evaluating the environmental performance of spreaders as it allows one to conduct an exhaustive evaluation of technologies, therefore preventing from pollution transfers, either from one impact category to another or from one step of the life cycle to another. In technology comparison and ecodesign [*24*], LCA is also value valuable because it makes it possible to compare technologies aiming at the same functions but having quite different paths for doing so, some being very innovative.

However, there are some limitation and points of attention to be aware of. LCA can be used at different scales, for instance, assessing the production of an agricultural good at a national level or on a given farm etc. The emission factors used for these 2 scales must not been the same. At a local scale (for instance for comparing 2 technologies), it is necessary to use tailored emission factors determined by measurement or simulation (what we have in the example above) in order to have relevant comparisons. Large scale emission factors (like IPCC ones) would not be appropriate as the result would not be discriminant enough. Any studies providing new data and methodology for doing so will have a great interest in LCA.

Therefore coupling LCA exhaustiveness to special focus on relevant emission factors and carrying out tests and simulations dedicated to refine these emission factors would be, according to us, the best way to develop an exhaustive but relevant environmental assessment of technologies.

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Figure 1 - The 4 steps of life cycle analysis

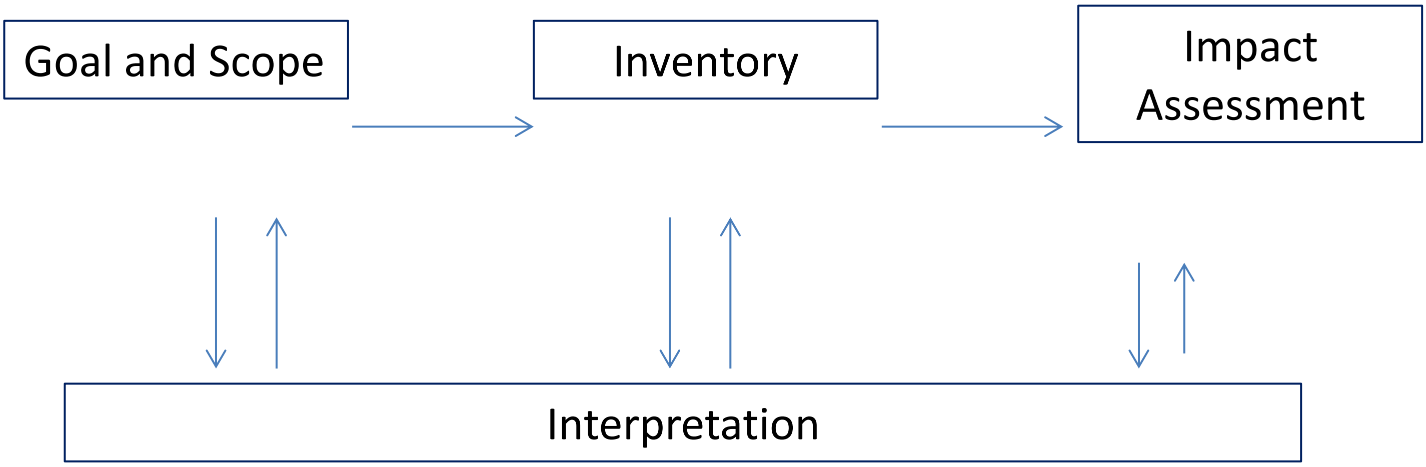

Figure 2 - The slurry spreading system under study by [*13*]

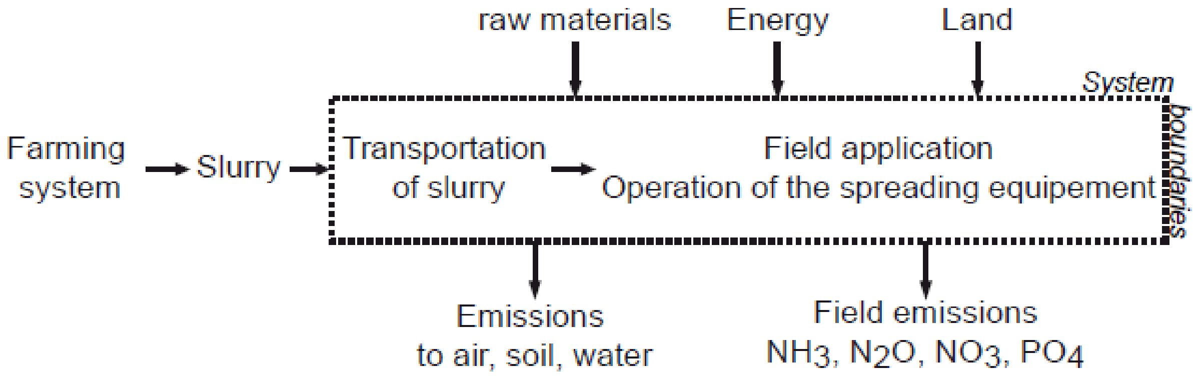

Figure 3 - Distribution of the relative N loss factors ki,j for NH_3 (left) and N_2O (right) for broadcast, harrowing and injection application techniques (from [*13*])

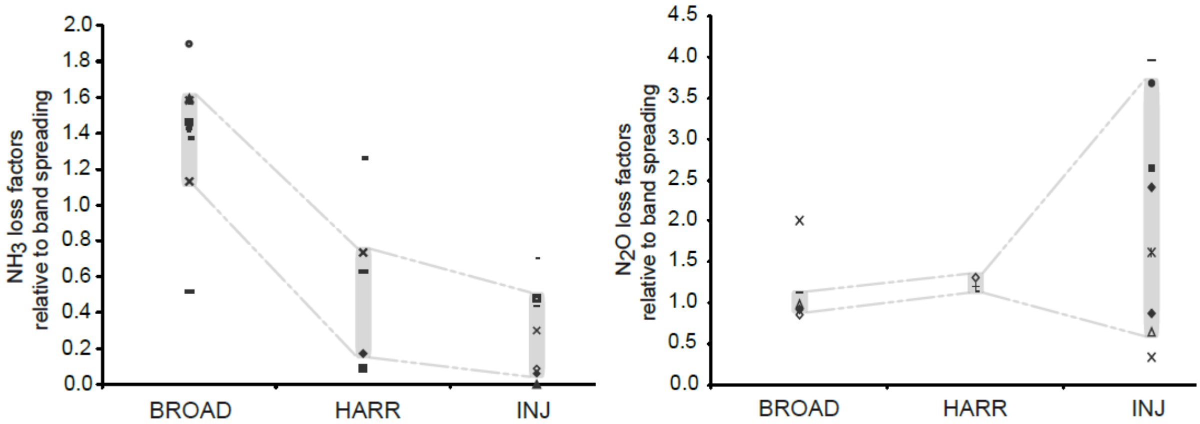

Figure 4 - Potential impacts expressed as a percentage of the ones of the Band Spreading scenario (from [*13*]).

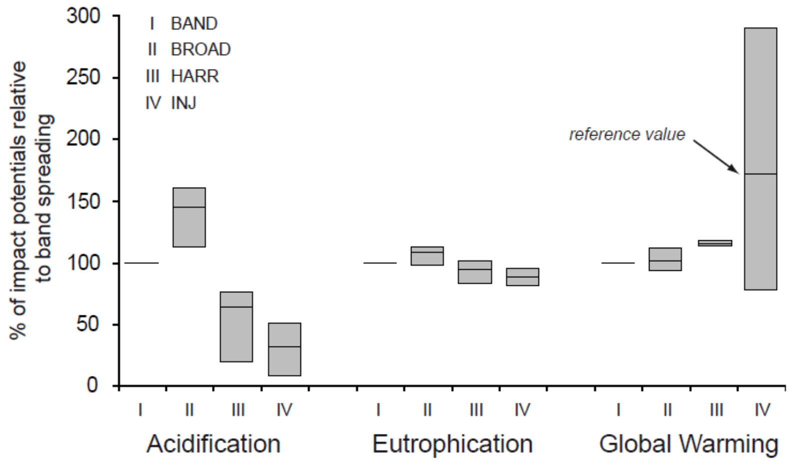

Figure 5 - Additional nitrogen flows due to uneven distribution (from [*14*])

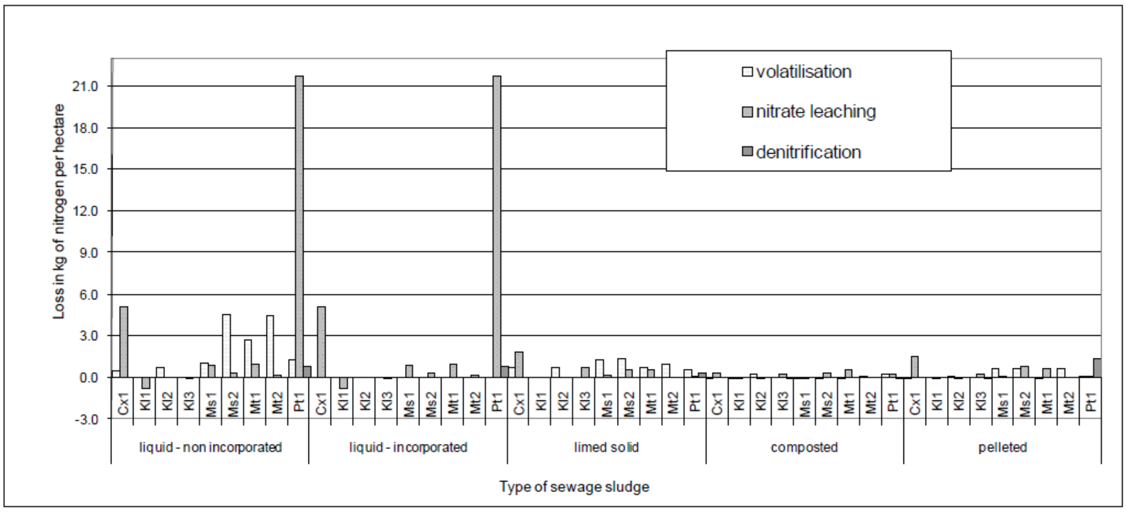

Figure 6 - Additional Nitrogen flows due to soil compaction (from [*14*])

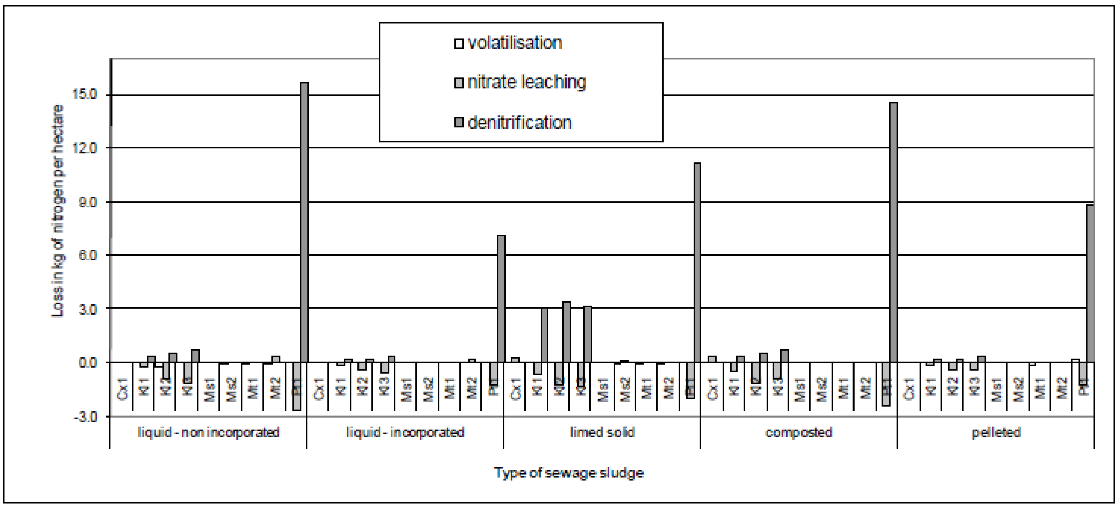

Table 1 - Characteristics of the spreaders used in the study carried out by [*13*]

Band spreading	Broadcast spreading	Harrowing	Injection
Tractor 80 kW	Tractor 80 KW	*2 passages*	100 kW tractor
10 m3 Slurry tanker	10 m3 Slurry tanker	Same equipments as for Broadcast spreading	10 m3 Slurry tanker
Trailing hoses	Splash-plate device	+	Injector
Speed : 4.5 km/h	*Speed : 4.5 km/h*	Tractor 100 kW	*Speed : 4 km/h*
Consumption : 8.5 l/h	*Consumption : 8.5 l/h*	Harrow	*Consumption : 8.5 l/h*
Working width= 12 m	*Working width= 9m*	*Speed : 2 ha/h*	*Working width= 3 m*
		Consumption : 13 l/h	

Table 2 - Nitrogenous emissions depending on the spreading technologies (from [*13*]).

	NH3			NO_3			total N_2O		
kg N	inf	med	sup	inf	med	sup	inf	med	sup
Band spreading		10.5			26.1			1.2	
Broad spreading	11.9	15.2	16.7	24.3	24.8	25.7	1.2	1.3	1.5
Harrowing	1.8	6.4	7.7	26.9	27.3	28.6	1.4	1.5	1.5
Injection	0.6	3.1	5.0	27.0	28.0	29.2	0.9	2.3	3.9

Table 3 - Description of the 9 sites in which the spreader performances are assessed with regard to nitrogen emissions (from [*14*]).

French site	Soil characteristics	Climate zone	Crop system rotation	Spreading period	Receiving crop
Montoldre (Mt1)	Sandy loam (74% sand, 18% loam, 9% clay)	Oceanic with temperate summer	Rape, winter wheat, winter barley	End of July	Winter barley
Montoldre (Mt2)			Rape, winter wheat, winter barley	August	Rape
Kerlavic (Kl1)	Loam (40% sand, 43% loam, 17% clay)	Oceanic	Winter wheat, Corn silage	End of February	Corn silage
Kerlavic (Kl2)			Winter wheat, Corn silage	March	Winter wheat
Kerlavic (Kl3)			Temporary grassland, Corn, winter wheat	End of February	Temporary grassland following by corn
Mons (Ms1)	Silt loam(5% sand, 74% loam, 19% clay)	Oceanic with continental influence	Sugar beet, winter wheat, winter barley	End of July	Sugar beet
Mons (Ms2)			NCC, sugar beet, winter wheat, winter barley	End of July	NCC† followed by sugar beet
Poitou (Pt1)	Chalky soil (40% sand, 30% loam, 30% clay calcium carbonate)	Oceanic	Rape, winter wheat, sunflower, winter wheat	August	Rape
Pays de Caux (Cx1)	Silt Loam (20% sand, 65% loam, 15% clay)	Oceanic	Fibre flax, NCC, sugar beet, winter wheat, winter barley	August	NCC followed by sugar beet

†NCC : Nitrogen Catch Crop

Table 5 - Description of the fertilizer / spreading machine pairs in study from [*14*]

Spreading machine	Sewage sludge type	Code
Slurry tank with splash plate	Liquid sewage	LS
Slurry tank with injectors	Incorporated liquid sewage sludge	ILS
Organic spreaders with vertical moving rotors	Solid lime sewage sludge	SLS
Organic spreaders with vertical moving rotors	Sewage sludge composted with green waste	CS
Organic Spreaders with spreading discs	Pelleted Sewage sludge	PS

Table 6 - Discrepancies between emission factors computed based on IPCC factors and simulated by our methodology.

			Simulated emissions with STICS and DEAC (kg.ha$_{-1}$)				Estimated emissions with IPCC factors (kg.ha$_{-1}$)				Variation			
	Site	Total nitrogen applied (TNA)	N-NH_3	N-NO_3	N-N_2O	total N	Nitrate leaching (0.3 * TNA)	N_2O direct emission = (0.01 * TNA)	N_2O indirect emission = (0.20 * kg N-NH_3 + 0.0075 * kg N-NO_3)	Total N_2O emissions	N-NO_3 kg N.ha^{-10}	N-NO_3 %	N-N_2O kg N.ha^{-10}	N-N_2O %
	Cx1	120.7	5.3	39	0	44.4	36.2	1.21	0.38	1.59	2.8	-7.7	-1.6	100.0
	Kl1	94.3	0	47.2	0.4	47.6	28.3	0.94	0.21	1.16	18.9	-66.8	-0.7	65.5
	Kl2	94.3	4.4	79.1	0.6	84.1	28.3	0.94	0.3	1.24	50.8	-179.5	-0.7	51.6
	Kl3	61.7	0	92.9	1.3	94.1	18.5	0.62	0.14	0.76	74.3	-401.6	0.5	-71.1
	Ms1	118.5	10.2	11.7	0	21.9	35.6	1.18	0.47	1.66	-23.8	67.1	-1.7	100.0
	Ms2	118.5	25	7.3	0	32.3	35.6	1.18	0.77	1.95	-28.3	79.5	-2	100.0
	Mt1	122	10.5	31.8	0	42.2	36.6	1.22	0.48	1.7	-4.8	13.1	-1.7	100.0
	Mt2	122	18.6	1.6	0	20.3	36.6	1.22	0.65	1.87	-35	95.6	-1.9	100.0
LS	Pt1	113.4	12	26.4	30.4	68.8	34.0	1.13	0.5	1.63	-7.7	22.4	28.8	-1765.0
	Cx1	120.7	4	39.7	0	43.7	36.2	1.21	0.35	1.56	3.4	-9.6	-1.6	100.0
	Kl1	94.3	0	47.2	0.2	47.4	28.3	0.94	0.21	1.16	18.9	-66.8	-1	82.8
	Kl2	94.3	1	79.6	0.3	80.9	28.3	0.94	0.23	1.18	51.3	-181.3	-0.9	74.6
	Kl3	61.7	0	93.5	0.9	94.3	18.5	0.62	0.14	0.76	74.9	-404.9	0.1	-18.4
	Ms1	118.5	7	11.8	0	18.8	35.6	1.18	0.41	1.59	-23.7	66.8	-1.6	100.0
	Ms2	118.5	11	7.3	0	18.3	35.6	1.18	0.49	1.67	-28.2	79.5	-1.7	100.0
	Mt1	122	2	31.9	0	33.9	36.6	1.22	0.31	1.53	-4.7	12.8	-1.5	100.0
	Mt2	122	5	1.4	0	6.4	36.6	1.22	0.37	1.59	-35.2	96.2	-1.6	100.0
ILS	Pt1	113.4	9	30.4	21.9	61.3	34.0	1.13	0.44	1.57	-3.6	10.6	20.4	-1294.9
	Cx1	150.5	4.6	29.9	0	34.5	45.1	1.5	0.43	1.94	-15.2	33.8	-1.9	100.0
	Kl1	117.6	0	49.4	3.1	52.5	35.3	1.18	0.26	1.44	14.1	-40.1	1.6	-115.3
	Kl2	117.6	2.6	78.8	3.5	84.9	35.3	1.18	0.32	1.49	43.5	-123.4	2	-134.9
	Kl3	79.3	0	92.2	3.7	96	23.8	0.79	0.18	0.97	68.5	-287.6	2.8	-281.4
	Ms1	147.6	16.8	10.1	0	26.9	44.3	1.48	0.67	2.14	-34.1	77.2	-2.1	100.0
	Ms2	147.6	16.8	6.6	0	23.4	44.3	1.48	0.67	2.14	-37.6	85.1	-2.1	100.0
	Mt1	152	5.5	30.5	0	36	45.6	1.52	0.45	1.97	-15.1	33.1	-2	100.0
	Mt2	152	10.4	0	0	10.4	45.6	1.52	0.55	2.07	-45.6	100.0	-2.1	100.0
SLS	Pt1	141.2	10.5	11.1	26.5	48.1	42.4	1.41	0.53	1.94	-31.2	73.8	24.6	-1266.0
	Cx1	157.1	6	23.7	0	29.7	47.1	1.57	0.47	2.04	-23.4	49.7	-2	100.0
	Kl1	122.8	1	49.6	0.4	51	36.9	1.23	0.3	1.52	12.7	-34.6	-1.1	73.7
	Kl2	122.8	2.3	81.9	0.6	84.7	36.9	1.23	0.32	1.55	45	-122.3	-1	61.3
	Kl3	168.7	0	92.3	1.3	93.6	50.6	1.69	0.38	2.07	41.7	-82.4	-0.8	37.2
	Ms1	154.1	15	9	0	24	46.2	1.54	0.65	2.19	-37.2	80.5	-2.2	100.0
	Ms2	154.1	15	5.3	0	20.3	46.2	1.54	0.65	2.19	-40.9	88.5	-2.2	100.0
	Mt1	158.7	3	31.4	0	34.4	47.6	1.59	0.42	2	-16.2	34.1	-2	100.0
	Mt2	158.7	9.1	0	0	9.1	47.6	1.59	0.54	2.13	-47.6	100.0	-2.1	100.0
CS	Pt1	147.6	12.3	8.8	26.1	47.1	44.3	1.48	0.58	2.05	-35.5	80.1	24	-1173.2
	Cx1	69.2	6	27.4	0	33.4	20.8	0.69	0.28	0.97	6.6	-32.0	-1	100.0
	Kl1	54.1	0	49.9	0.2	50.1	16.2	0.54	0.12	0.66	33.7	-207.5	-0.5	69.7
	Kl2	54.1	2.1	81.6	0.3	83.9	16.2	0.54	0.16	0.7	65.4	-402.8	-0.5	57.1
	Kl3	74.2	0	92.9	0.9	93.8	22.3	0.74	0.17	0.91	70.6	-317.3	0	1.1
	Ms1	68	17.6	9.1	0	26.7	20.4	0.68	0.51	1.19	-11.3	55.4	-1.2	100.0
	Ms2	68	17.6	5.7	0	23.4	20.4	0.68	0.51	1.19	-14.7	72.1	-1.2	100.0
	Mt1	70	3.9	31.6	0	35.5	21.0	0.7	0.24	0.93	10.6	-50.5	-0.9	100.0
	Mt2	70	8.6	0	0	8.6	21.0	0.7	0.33	1.03	-21	100.0	-1	100.0
PS	Pt1	64.9	11.3	10.9	27.1	49.3	19.5	0.65	0.37	1.02	-8.6	44.0	26.1	-2556.9