Environmental systems analysis of agricultural systems: Coupling dynamic simulation models with Life Cycle Assessment

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ABSTRACT

Life Cycle Assessment (LCA) is usually carried out using fixed coefficients for resource use and emissions as the basis for the calculation of the environmental impact of a product or a service. However, in agriculture, where the systems' functioning largely depends on the dynamic organisation of agricultural practices and on variable climatic conditions, coupling dynamic simulation models with LCA seems necessary. This paper presents the combination of a dynamic simulation model and LCA to assess the environmental impact of a collective pig slurry management system. The model simulates the production of slurry, its stock level in storage facilities, its transport and application to crop fields, as well as the gaseous emissions occurring in these stages, under different management strategies and climatic conditions. Results from the combination of these approaches show the great variability of the agronomic and environmental performance of the collective slurry management system in relation to different organisational schemes, agronomic decisions and climatic conditions.

OBJECTIVE

Life Cycle Assessment (LCA) has gained popularity in the last decade for the environmental evaluation of a product or service and it is used by scientist and professionals from a wide range of fields and disciplines. LCA is normally carried out as a steady state method where fixed coefficients of resource use and emissions are used for the inventory analysis and fixed characterization factors are used for the impact assessment.

In agriculture, however, the functioning of a system largely depends on (i) the dynamic organisation of agricultural practices and (ii) the variable climatic conditions. The combination of these determinants can strongly affect the agronomic and environmental performances of agricultural systems. For this reason, envisaging the coupling of dynamic models and LCA seems a promising way to better understand the intertwined technical and environmental performances of agricultural systems.

The aim of this paper is to show the combination of such modelling and assessment approaches. A specific example of a collective pig slurry management system is shown. The dynamic model simulates the production of slurry, its stock level in storage facilities, its transport and application to crop fields, as well as the gaseous emissions occurring in these stages, under different management strategies and climatic conditions. Results from the dynamic model serve as input for the inventory analysis of an LCA of collective slurry management scenarios.

METHOD

The context of the study

In Brittany, Western France, nitrogen (N) in the form animal manure surpasses crop needs of the region. This represents an important environmental hazard as its mismanagement threatens the quality of water resources and contributes to the emissions of NH_3, CH_4 and N_2O. Under current French regulations, excess manure has to be treated or exported to other regions for its application to crop land [1].

In the Southeast of Brittany, a group of pig farmers has proposed a collective pig slurry transfer plan. In this plan, 57.6 Mg as N of pig slurry belonging to 11 pig farmers will be transferred to a group of 22 crop farmers, at a distance ranging from 33 to 55 km and applied to different crops (winter cereals –wheat and triticale-, grain and silage maize, oilseed rape and grassland).

System dynamics and the COMET model

The system under analysis includes only the excess slurry to be transferred and takes into account the production, storage, collection, transportation and application of slurry [2]. The dynamic model (COMET – COllective management Model for environmental and logistic Evaluation of manure Transfer plans), simulates these stages of excess slurry management as well as the gaseous emissions (NH_3 and CH_4) during slurry storage and application. COMET, programmed in VENSIM®, is the product of the integration of other stand-alone models [3,4,5].

In COMET, the production of slurry is considered a continuous process, temporarily stored in the under slatted floor pits and emptied by batches every 36 days to external storage tanks. During storage, NH_3 and CH_4 are the main gaseous emissions and, in COMET, they are calculated on a daily time step. Emission factors from Loyon *et al*. [6] has been corrected by slurry nitrogen content (for NH_3) and by temperature (for the two gases) using equations from Pelletier *et al*.[7].

Each tank storing slurry is emptied by trucks that carry it from the pig farms to intermediate storage facilities in the spreading region. These storage facilities are covered and therefore no gaseous emissions occur. The supply from the pig farms to the intermediate storage is based on one of the policies described in Guerrin and Médoc [8]: (i) a delivery is tentatively triggered when the intermediate storage tank is below a lower level; (ii) the choice of the pig farm to be collected first is based on its slurry stock level, transportation distance and size (*i.e.* the fullest, furthest, biggest farm is collected first).

The calendar for slurry application to crops is defined by crop management and national regulations (slurry application is forbidden at various periods for different crops and during weekends). Surfaces and doses of slurry for the different crops are defined in an agreement between the pig and crop farmers according to fertilisation schemes provided by the crop farmer for each crop. In COMET, two priority rules are implemented to define the crop fields to spread: a priority based on crop type: winter cereal > oilseed rape > maize > grassland and, among fields with same crop, a priority on the degree of fulfilment of the N to be applied (i.e. the largest deficit first).

The feasibility of entering fields to spread is driven by climatic conditions and scenarios are built with different rules based on present and previous rainfall (RR) and potential evapo-transpiration (PET) (Table 1). Based on technical advisers' experience, two criteria are defined: the RR-PET of the current day (called RPd) and the ten days moving average of RR-PET (called RPa). Two rules to enter the fields are defined: when it rains (i.e. RPd > 0), it is not possible to spread and the slurry can be applied after a delay defined according to the advisors' knowledge of crop and soil types (Table 1). The delay depends on the value of RPa relative to two thresholds (0 and 2 mm in our simulations) and on the spreading capacities according to the soil types (hydromorphic *vs* well drained soil) and soil cover (cereals *vs* grassland). Spreading is performed by a Terragator® before soil tillage for maize and oilseed rape and just after tillering for winter crops and grassland.

NH_3 emission after spreading is simulated with STAL parameterised for Brittany [5], with a 80% emission reduction due to slurry injection into the soil [9].

The Life Cycle Assessment model

An LCA model for the transfer of excess slurry has been developed which is fully described in Lopez-Ridaura et al [1]. The functional unit of analysis is one m^3 of slurry transferred and the phases included in the model are the on-farm storage of slurry, its transport and intermediate storage and its application to crop land. The inventory analysis includes resource use, such as concrete for the storage tanks, steel for making transport and spreading units and diesel used for slurry transport and application. Also, as slurry is used as organic fertilizer for crops, chemical fertiliser saved by slurry application is subtracted from the environmental impact of the slurry transfer scenarios.

Instead of using fixed coefficients for CH_4 emissions during slurry storage, and NH_3 emissions during slurry storage and application, the results of COMET simulations are used. Also, the amount of chemical fertiliser saved by slurry application is calculated by COMET after discounting all N losses. N_2O emissions after slurry application is considered to be 2% of the total N applied to crop land [10].

Total (direct, indirect and avoided) emissions and resource use are aggregated and expressed in terms of four impact categories: Eutrophication (in kg PO_4–eq.), Acidification (in kg SO_2–eq.), Climate Change (in kg CO_2 –eq.) and Non-Renewable Energy Use (in MJ of Lower Heating Value (LHV)-eq.). For the quantification of indirect resource use and emissions, the BUWAL 250 [11] , ETH-ESU [12] and IDEMAT [13] databases were used as implemented in SimaPro 6 [14].

The assessed scenarios

Eight scenarios of collective slurry transfer were evaluated by coupling the use of COMET and the LCA model. These scenarios are built as a combination of two soil types determining access to fields for spreading (Well Drained -WD- -and Hydromorphic -H-), two levels of spreader availability (3 or 5 days per week) and two climatic years in relation to rainfall (2001 with a wet late winter and 2002 with a dry one) (Table 1). A reference scenario is also evaluated in which fixed coefficients for gaseous emission during storage and application of slurry and an average storage time of 82 days is used as reported in Lopez-Ridaura et al. [1].

Table 1. Scenarios evaluated and delay imposed for accessing the fields in relation to rainfall

	Delay before spreading (days) in relation to RR-ETP (mm)					
	Cereals			Grassland		
Scenarios	<0	0-2	>2	<0	0-2	>2
WD -5 - 2001	0	2.5	5	0	1	2.5
WD -5 - 2002	0	2.5	5	0	1	2.5
WD -3 - 2001	0	2.5	5	0	1	2.5
WD -3 - 2002	0	2.5	5	0	1	2.5
H -5 - 2001	1	4	7	0.5	2	4
H -5 - 2002	1	4	7	0.5	2	4
H -3 - 2001	1	4	7	0.5	2	4
H -3 - 2001	1	4	7	0.5	2	4

RESULTS

Figure 1 shows results obtained with the COMET model. It shows, for two scenarios, the storage level of excess slurry for the group of pig farmers and the emissions of CH_4 during storage. The difference between the two scenarios is due to rainfall conditions; in wet years like 2001, access to fields for slurry spreading is limited and therefore a larger volume of slurry is stored longer, thus increasing overall CH_4 emissions.

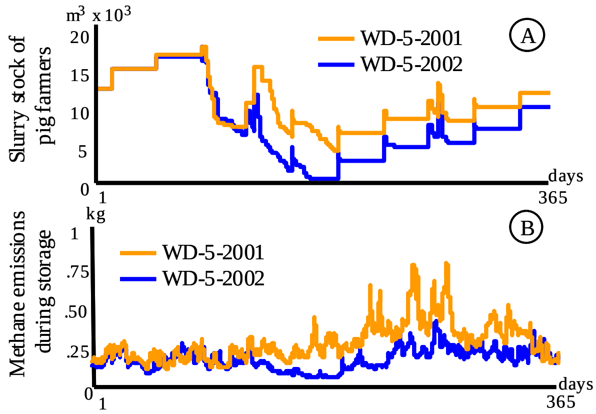

Figure 1. Daily slurry stock levels (A) and methane emissions (B) for two scenarios of collective slurry management as simulated by COMET

Table 2. Emissions and N substituted from chemical fertilisers for eight scenarios simulated by COMET

Scenarios	Emissions (kg m^{-3})			substituted N from fertiliser (kg m^{-3})
	NH_3	N_2O	CH_4	
WD -5 - 2001	1.15	0.16	4.17	3.28
WD -5 - 2002	1.13	0.16	3.70	3.29
WD -3 - 2001	1.41	0.15	6.76	3.14
WD -3 - 2002	1.17	0.16	6.19	3.27
H -5 - 2001	1.35	0.15	4.79	3.17
H -5 - 2002	1.14	0.16	3.77	3.29
H -3 - 2001	1.57	0.15	9.27	3.05
H -3 – 2001	1.44	0.15	7.15	3.13

Table 2 shows the NH_3, N_2O and CH_4 emissions and the N from fertilisers substituted by the slurry for eight scenarios and Figure 2 shows the results of these scenarios for the four impact categories with respect to the reference scenario (normalised at 1).

DISCUSSION AND CONCLUSIONS

The results for the eight scenarios show the diversity of the environmental performances of the slurry transfer plan in relation to agronomic and logistic decisions and climatic conditions. When slurry is spread on well drained soils and the spreader is available for 5 days a week, there are no important differences between climatic years as spreading is not limited. However, in comparison to the reference scenario, where fixed storage time and emissions are assumed, these scenarios show more impact on eutrophication and acidification and less on climate change implying that, in the reference scenario, CH_4 emissions during storage were overestimated and NH_3 emissions underestimated, especially at spreading.

When slurry application is limited by either the availability of spreader or soil conditions, climatic conditions strongly affect the environmental performance of the collective plan for excess slurry transfer. Thus, scenarios for wet years like 2001 have a poorer environmental performance than their dry year (2002) counterparts (i.e. over 20% impact increase for some categories). Scenarios where spreading is limited by either soil conditions or spreader availability, have up to twice the environmental impact of the reference scenario for some categories.

It has been shown that slurry transfer represents a net saving of energy due to the substitution of chemical fertilisers [1]. Between the scenarios simulated with COMET there are no mayor differences in energy use as differences in N substituted from chemical fertilizer are only between 3 and 8% and the energy used for transport

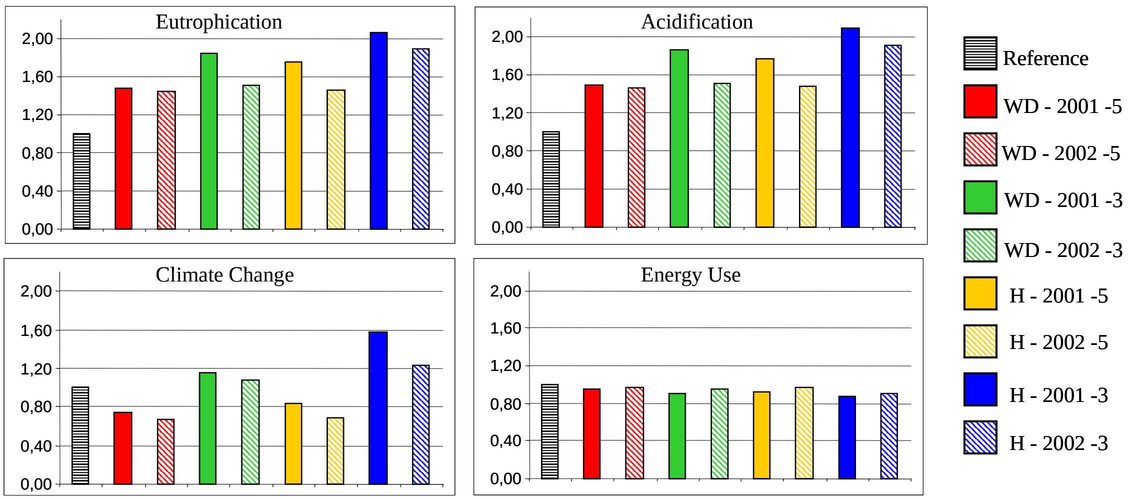

Figure 2. Results from the LCA for eight scenarios of collective slurry management in relation to a reference scenario

and application of slurry, applicable equally to all scenarios, levels off the energy use.

The scenario analysis presented here shows the importance of coupling dynamic modeling approaches and LCA for the environmental analysis of agricultural systems where agronomic and logistic decisions, as well as climatic conditions, represent the mayor determinants for their performance. The system evaluated here, limited to manure management, is only a small part of an agricultural production system. Expanding the boundaries of such a system to, for example, livestock and crop productions might increase the variability of its environmental performance related to changes in many more agronomic and climatic aspects.

Using average fixed coefficients for the inventory analysis in the LCA of agricultural systems may result in erroneous assessments of the environmental performance of specific practices. Also, climatic conditions and agricultural practices may affect the fate of pollutants in the environment. Therefore, characterization factors for impact assessment should also be simulated to improve our understanding of the variability of the environmental performance of agricultural systems [15].

Coupling dynamic simulation models and LCA is a promising approach to assess the impact of organisational schemes, agronomic decisions and climatic conditions on the agronomic and environmental performance of agricultural systems.

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