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Agron. Sustain. Dev. (2015) 35:347–358
DOI 10.1007/s13593-014-0248-z

RESEARCH ARTICLE

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Brigitte Langevin · Sophie Génermont · Claudine Basset-Mens · Laurent Lardon

Accepted: 23 July 2014 / Published online: 9 September 2014

Abstract Land application of manures and slurries are a major source of pollution such as water contamination by nitrates and greenhouse gas emissions. NH_3 and N_2O emissions can be lowered by suitable spreading techniques. However, a comprehensive review of the impact of slurry spreading techniques is lacking. For that we developed a model, named OSEEP, that simulates the effect of slurry incorporation, slurry spatial distribution, and soil compaction on NH_3 and N_2O emissions. OSEEP integrates a soil compaction model, a hydraulic pedotransfer function, a NH_3 volatilization model, and a crop model. We ran OSEEP for five sites in France for 7 years. Four techniques were simulated: broadcast spreading, band spreading, incorporation after surface spreading, and injection. We tested various sizes of slurry tankers and tractors. We calculated NH_3 and N_2O relative emissions from various spreading techniques with respect to band spreading. Results show good agreement between model calculation and published field data. We found that slurry applied by a self-propelled 15-m^3 tanker with extra large tires led to an increase of 20 % in N_2O emission, by comparison with a 15-m^3 tanker trailed by a tractor. Hence, we show that soil compaction should be taken into account to optimize trade-offs between NH_3 and N_2O emissions.

Keywords Slurry application · Spreading techniques · Modeling · Ammonia · Nitrous oxide · Field emissions

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1 Introduction

Nitrogen (N) supply is a key issue in agriculture. While allowing the tripling of global food production during the past 50 years (Mosier et al. 2004), N supply also caused a cascade of damages due to excessive losses of reactive N in the environment (Galloway and Cowling 2002). Ammonia (NH_3) and nitrous oxide (N_2O) are two major gaseous pollutants from agricultural activities (Peoples et al. 2004). Ammonia is responsible for eutrophication, soil acidification, and changes in the biodiversity of seminatural ecosystems, as well as for increased emissions of nitrous oxide (Peoples et al. 2004). Ammonia also participates in the formation of small-size aerosols which affect human health (EMEP-EAA 2009). Nitrous oxide is a very potent greenhouse gas and was also found to have a deleterious effect on the stratospheric ozone layer (Galloway and Cowling 2002).

With the specialization of farming systems, manure and slurries have become major sources of N pollutants. Their proper handling is important to reduce the environmental impacts of agriculture and to preserve their fertilizing value (EMEP-EAA 2009; IPCC 2006). For this reason, manufacturers seek to design environmentally friendly spreaders by taking into account both customers' demands, such as the working rate or costs, and environmental impacts.

Many investigations were performed primarily to reduce NH_3 losses from slurry spreading (Fig. 1), but there was a concern that NH_3 reduction might result in greater N losses via other pathways (Dosch and Gutser 1996; Hansen et al. 2003; Smith et al. 2000; Webb et al. 2010). Field experiments were thus conducted to assess the impact of slurry spreading techniques on both NH_3 and N_2O emissions (Vandré et al. 1997; Weslien et al. 1998; Wulf et al. 2002a). These investigations showed a consistent trend about the abatement efficiencies of spreading techniques on NH_3 emissions (EMEP-EAA 2009; Sommer and Hutchings 2001; Webb et al. 2010). Yet, there is no consensus about the importance of N_2O emissions, probably because this emission is greatly influenced by interacting environmental variables (Peoples et al. 2004; Velthof et al. 2003). In this context, modeling is a good mean to explore the impact of spreading techniques on the N cycle in agro-ecosystems. Indeed, models can single out the effect of farming practices and more generally help designing new cropping systems (White et al. 2011). Yet, no universal model applies to the diversity of agricultural contexts and user's objectives (Boote et al. 1996). Models accounting for the techniques of slurry spreading were developed to predict NH_3 volatilization (Génermont and Cellier 1997; Søgaard et al. 2002) but not N_2O losses. More general crop models that predict N_2O emissions, such as STICS (Brisson et al. 2008), do not take into account the spreading techniques of manure or slurry. Therefore, we developed a modeling approach to simulate the impact of slurry spreaders on both NH_3 and N_2O emissions. Our approach is based on linking existing models. The challenge implied integrating models developed in different contexts. We also developed a method to compare the outputs of the integrated model with field measurements from the literature, as no field experiments were planned to test the model.

The modeling and testing approaches can be generalized to other farming practices. The primary goal is to generate the data necessary to conduct prospective studies assessing farming practices at less cost, not to improve agro-environmental models. Our model offers an alternative when no or little data is available to perform environmental assessment, such as life cycle assessment (Langevin et al. 2010). Indeed, life cycle assessments rely on numerous data. Practitioners facing a shortage of data often use the same data for a country or a continent, which may lead to inconclusive results (Payraudeau et al. 2007). Moreover, recent applications of life cycle assessment in South countries are generally conducted in situations where data are extremely scarce (Perrin 2013).

The paper presents the following: (1) the identification of the most important effects of slurry spreading techniques on field NH_3 and N_2O emissions; (2) the selection of models to simulate those selected effects and their integration into a global model named OSEEP (Outil de Simulation des Effets des Epandeurs sur les Pertes azotées); (3) a testing method for OSEEP using relative emission factors; (4) the comparison of OSEEP outputs with experimental measurements from the literature; (5) four examples of OSEEP applications to design environmentally friendly spreaders; and (6) a generalization of the approach to other farming practices.

Fig. 1 Broadcast application of slurry

2 Materials and methods

2.1 Model development

2.1.1 Selection of the main potential effects of application techniques on NH_3 and N_20 emissions

We considered two main N emissions causing adverse effects on the environment: ammonia and nitrous oxide (Peoples et al. 2004). We excluded nitrate from the analysis because there was too little data to test OSEEP capacities to simulate nitrate leaching. Langevin (2010) conducted a literature survey about the emission mechanisms of NH_3 and N_2O and the key factors governing them. The extent to which a spreading technique affects N emissions was also assessed from field trials reported in the literature. Based on the data collected, three main features affecting N emissions during spreading were identified: incorporation of slurry into the soil, spatial distribution of slurry over the field, and soil compaction in the wheeling tracks.

Incorporation of slurry Incorporation of surface-spread slurry or direct injection of slurry into the soil has a drastic action since NH_3 is not likely to volatilize once the slurry is no longer in contact with the atmosphere (Sommer and Hutchings 2001). The reduction of NH_3 emission for shallow injection with respect to broadcast spreading ranges from 23 to 94 % on arable lands and from 60 to 99 % on grasslands; the reduction of NH_3 emissions reaches 95–99 % for deep injection on arable lands (Webb et al. 2010). Yet, slurry incorporation is expected to cause higher N_2O emissions (Bessou et al. 2010) due to the substantial increase of N and C substrates when slurry is applied in slots.

Spatial distribution of slurry Spreading devices such as trailing hoses, that deposit the slurry in bands over about 30 % of the field surface, limit NH_3 emissions by reducing the area of slurry exposed to the atmosphere (Sommer and Hutchings 2001). Band spreading allows an average reduction in NH_3 losses of about 40 %, ranging from 0 to 75 % (Søgaard et al. 2002; Webb et al. 2010). As slurry incorporation, the application of slurry in bands or unevenly over the surface results in locally variable amounts of water, N and C substrates, that also directly affect N_2O emissions.

Soil compaction in the wheeling tracks The wheels of the spreading machines compact the soil and increase the percentage of soil pore space filled with water. As a result, N_2O emissions may increase due to a higher denitrification (Bessou et al. 2010). By impeding slurry infiltration, compaction will also affect NH_3 emission, which can double in the case of a poor soil infiltration (Sommer and Hutchings 2001; Garcia et al. 2012).

2.1.2 Selection of models

Outline of the model We relied upon the work of Cannavo et al. (2008) to find suitable models to account for the effects of slurry incorporation, slurry spatial distribution and soil compaction on NH_3 and N_2O emissions. We did not find a single comprehensive model able to simulate the three effects. A crop model is mandatory to estimate the different dynamics of N pools, which are controlled by processes such as heat and water transfers, the cycling of organic matter, the growth of crops and their uptake of water and nitrogen. We thus searched for a generic crop model. We subsequently tried to simulate the three identified effects of application techniques with the crop model alone, or with the addition of other models.

We selected the dynamic crop model STICS (Brisson et al. 2008), which predicts the impact of soil and climate conditions, as well as agricultural practices, on crop production and environmental variables. We chose STICS because (1) it is robust, i.e., able to simulate various soil and climate conditions without considerable bias in the outputs; (2) we had all the input data to feed the model and (3) the STICS developers offered training sessions and a continuous scientific support. STICS is able to simulate NH_3 volatilization and N_2O emissions from denitrification. However, STICS time-step is 1 day and therefore cannot simulate the incorporation of slurry a few hours after spreading. Hence, we selected Volt'Air (Génermont and Cellier 1997), a mechanistic model predicting NH_3 volatilization at the field level after slurry spreading on bare soil. Volt'Air makes it possible to finely tune the parameters relative to slurry incorporation, such as the timing and depth of incorporation. Moreover, it is possible to adjust Volt'Air input parameters to simulate soil compaction.

Volt'Air was designed for slurry application on bare soil and thus does not account for the crop cover. We selected the algorithm developed by Thorman et al. (2008), which simulates the effect of a crop cover after band spreading. This algorithm is simple: it uses a reduction factor for NH_3 emission depending on the crop height.

STICS, Volt'Air, and the crop canopy reduction factor may be combined as a sequence of models, first quantifying NH_3 emissions, which is the first nitrogen loss pathway (Génermont and Cellier 1997), and subsequently N_2O emissions from denitrification (Fig. 2). All models were run from the day of application. As the STICS module for volatilization could not be modified, we separated the slurry into two phases, a remaining mineral phase and an organic phase. The N amount of the mineral phase was reduced with the quantity of NH_3 losses. The mineral phase was entered in STICS as ammonium nitrate below the soil surface, causing no additional NH_3 losses. The organic phase was entered at the simulated depth of slurry placement. Since nitrification is generally a rapid process in a temperate climate, STICS converted all mineral N to nitrate (Brisson et al. 2008).

Both the performance and domain of validity of the integrated model are discussed in "section 2.1.3".

Incorporation of slurry The typical time-step of Volt'Air is 1 h, thus the simulation of incorporation at various times after spreading is possible. The linkage of models is shown in Fig. 2a. The input data are the time and depth of incorporation as well as the proportion of slurry incorporated. The effect of slurry incorporation on N_2O is taken into account indirectly through the remaining N in the slurry that has not volatilized.

Slurry spatial distribution Volt'Air has recently been adapted to account for discontinuous applications of slurry (Garcia et al. 2012). However, neither Volt'Air nor STICS in their current versions simulate directly the effect of an uneven distribution of the slurry over the field. In order to simulate this effect, we constructed a histogram of the spatial distribution of slurry, i.e., a set of local doses of applied slurry and their frequency. Histogram of local doses applied by spreaders can be considered as a normal distribution (Langevin 2010; Thirion and Pradel 2010). We then generated several normal distributions with various values of standard deviations, with a mean value set to the applied dose over 1 ha. The models were run for each value of the histogram. The resulting N losses were integrated to obtain the global N losses for the entire field (Fig. 2b).

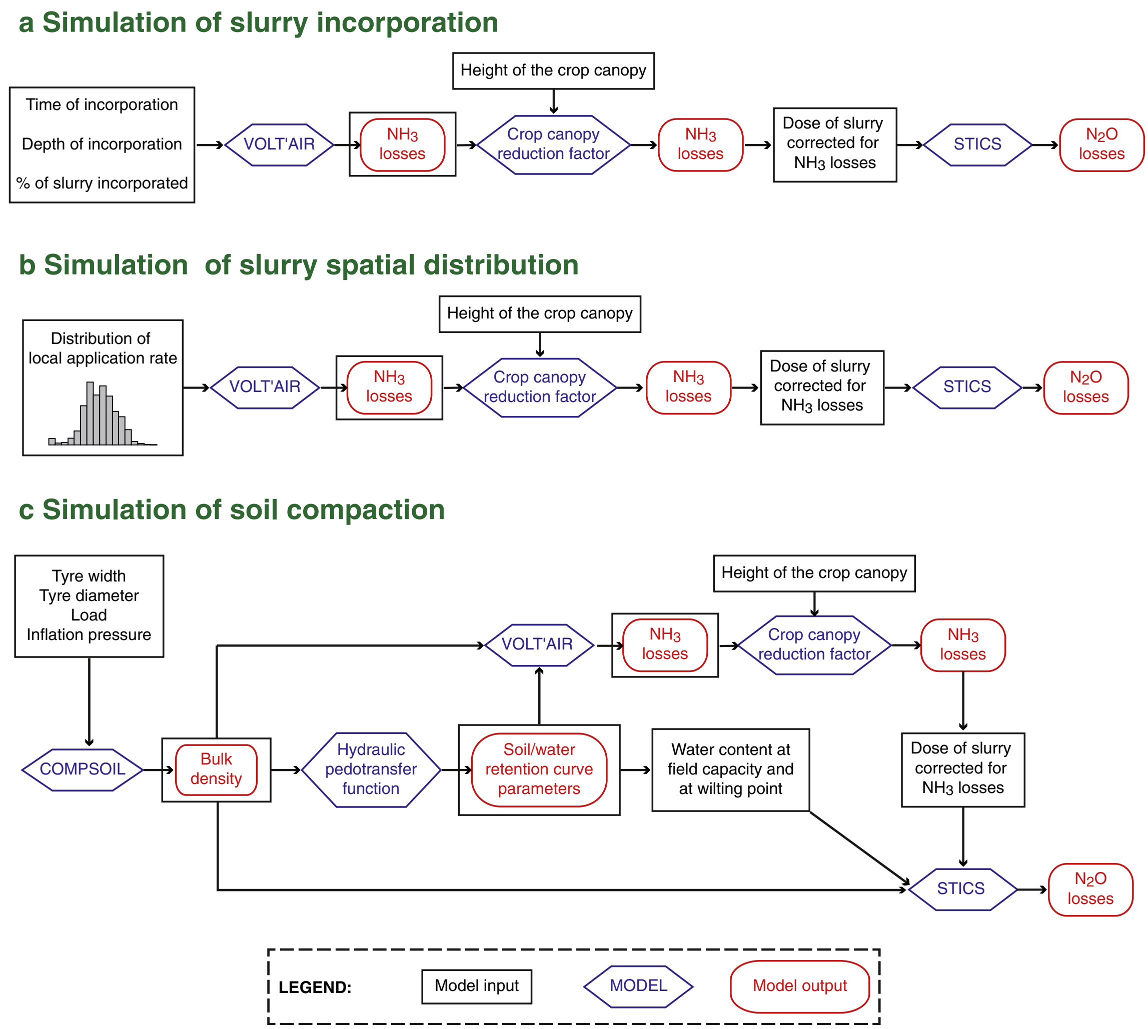

Fig. 2 Integration of models to simulate the effects of slurry application techniques on NH_3 and N_2O emissions. In a first step, Volt'Air simulates the total NH_3 volatilization. A reduction factor can be applied on the NH_3 emission to account for a possible crop cover. In a second step, STICS simulates N_2O emissions from an application of slurry whose ammonium content has been reduced with the quantity of NH_3 losses. Slurry incorporation is simulated directly though Volt'Air input data. The spatial distribution of slurry is simulated by running OSEEP for each value of a histogram of local doses of slurry; the resulting emissions are then integrated over the entire field. Soil compaction is simulated with Compsoil, which calculates the resulting bulk density under the wheel track. A pedotransfer function accounting for the bulk density is used to adjust the soil hydraulic parameters of Volt'Air and STICS

Soil compaction A routine for soil compaction was added in STICS for sowing and harvesting (Brisson et al. 2008), but not yet for slurry or manure application during crop growth. Furthermore, Volt'Air does not take into account the effect of soil compaction by agricultural traffic on NH_3 losses. In order to account for soil compaction, we followed a three-step approach (Fig. 2c):

(1) We identified the input data of Volt'Air and STICS affected by soil compaction: the soil hydraulic parameters and the soil bulk density. The idea was to first simulate the impact of the slurry spreaders on the soil bulk density and in a second step, to use pedotransfer functions accounting for bulk density when predicting soil hydraulic parameters. Volt'Air hydraulic input parameters are the saturated hydraulic conductivity and the van Genuchten's parameters of the soil-water retention curve (van Genuchten 1980). On the other hand, STICS uses permanent hydraulic characteristics: the gravimetric soil water contents at field capacity and at wilting point, the soil bulk density, and an infiltrability parameter (Brisson et al. 2008).

(2) In order to simulate the soil compaction by slurry spreaders, we selected Compsoil (O'Sullivan et al. 1999) which is a simplified and user-friendly analytical model. Compsoil input parameters are as follows: (i) the tire width and diameter, load and inflation pressure; (ii) the profile of the soil bulk density and the profile of the soil water content, and (iii) three mechanical parameters describing the virgin compression line and rebound line

(O'Sullivan et al. 1999). Pedotransfer functions are available to estimate Compsoil mechanical parameters (Défossez et al. 2003; Saffih-Hdadi et al. 2009). Compsoil calculates the dry bulk density profile under the centerline of a wheel track and also gives the depth of the resulting rut. A mean value of bulk density of the compacted soil was subsequently calculated for the 0–30-cm layer. But note that a finer discretization of the soil bulk density profile may be used.

(3) In order to simulate the effect of soil compaction on hydraulic properties, we reviewed the pedotransfer functions using the soil bulk density when predicting soil hydraulic properties. We selected the pedotransfer function developed by Wösten et al. (1999). This pedotransfer function predicts the saturated hydraulic conductivity and the parameters of van Genuchten's water retention curve from the soil textural composition, organic matter content, and bulk density. The soil hydraulic parameters of Volt'Air were directly estimated with this pedotransfer function. The gravimetric soil water contents at field capacity and at wilting point used in STICS were subsequently calculated with the van Genuchten's water retention curve equation (van Genuchten 1980). The value of the infiltrability parameter in STICS was calculated with a linear interpolation from values given by Brisson et al. (2008).

2.1.3 Performance and domain of validity of OSEEP

The three effects of the incorporation of slurry, the slurry spatial distribution, and the soil compaction were then integrated into the comprehensive model OSEEP. Our aim was to simulate the global effect of slurry spreaders using various application techniques, such as band spreading or slurry injection. The performance and the domain of validity of OSEEP depend on the individual performance and domain of validity of each of the linked models.

Cannavo et al. (2008) reviewed papers assessing the performance of models simulating N processes. Twenty-one published papers found that STICS capacities to simulate experimental data were satisfactory for several N processes and crop growth. Yet, the predictive capacity of both STICS submodel for denitrification and the Volt'Air model is still debated (Cannavo et al. 2008). However, the same authors found, as a general rule, that the modeling of the denitrification and volatilization processes were less accurate as compared to nitrate leaching, mineralization, nitrification, and N uptake by plants. Regarding the sensitivity to input data, Vol'Air is particularly sensitive to the soil pH (Génermont and Cellier 1997; Smith et al. 2009). Both NH_3 and N_2O emissions are especially sensitive to the soil-water content as a consequence of the sensitivity of Compsoil, Volt'Air, and the STICS submodel for denitrification to the soil water content (Brisson et al. 2008; Génermont and Cellier 1997; Hénault and Germon 2000; Langevin 2010; O'Sullivan et al. 1999).

Regarding the domain of validity of OSEEP, the application of the integrated model is obviously restricted to the conditions under which all models can be used. STICS was designed to be robust, i.e., able to simulate various soil and climate conditions without significant bias on the results (Brisson et al. 2008). Similarly, Volt'Air, a mechanistic model, and Compsoil, a semi-analytical model, are applicable in a wide range of conditions. However, we also used two empirical models, which are valid only in the conditions under which they were calibrated. The first empirical model is the pedotransfer function that estimates the soil hydraulic parameters. The selected pedotransfer function was built from an extensive database gathering 4,030 soil horizons from 12 European countries (Wösten et al. 1999). This pedotransfer function should therefore be valid for most European soil types. The second empirical model is the reduction factor that accounts for the effect of the crop canopy on NH_3 emissions. The model was developed for band application techniques in Denmark and Southern England, with crop cover above 15 cm. The simulations will then be less accurate for broadcast-applied slurry and under drier climatic conditions, e.g., in Southern Europe. However, note that band applications are preferred to broadcast applications when the vegetation is well developed. In conclusion, OSEEP is applicable (i) on bare soil for a wide range of conditions relative to the soil, climate, slurry, and application techniques and (ii) on crop-covered soil with a canopy >15 cm for band application techniques under oceanic climate. Band application techniques refer to application with trailing hoses, trailing shoes, with or without soil incorporation, or directly injected into the soil.

2.2 Model testing

2.2.1 Case study

OSEEP simulated a mid-February application of 30 m^3 ha^{-1} of pig slurry in five sites in France during 7 years, from 2002 to 2008. Weather data were collected from Climatik, the INRA network of weather stations. The pig slurry had a dry matter content of 4 %, a pH of 7.12, a total ammoniacal N of 2.5 g kg^{-1} for a total N of 3.5 g kg^{-1}. The sites were (a) Kerlavic (48°00′ N, 4°06′ W), Britanny, characterized by a loamy soil, an oceanic climate, and by an excess of slurry production; (b) Mons-en-Chaussée (49°80' N, 3°60' E), north-eastern France, a loess soil sensitive to soil compaction; (c) Châlons en Champagne (48°50′ N, 4°22′ E), eastern France, a limestone soil with continental climate; (d) Montoldre (46°39′ N, 3°15 E), central France, a sandy loam soil with poor water retention capacity; (e) Auzeville (43°32′

Table 1 Key characteristics of the five simulated sites

	Kerlavic	Mons	Châlons	Montoldre	Auzeville
Clay <2 μm (%)	17	20	31	9	27
Silt 2–50 μm (%)	43	75	41	18	35
Organic matter content (%)	3.4	1.7	3.3	1.3	1.7
pH	5.8	7.8	8.3	6.5	6.6
Dry bulk density (g cm^{-3})	1.24	1.30	1.23	1.48	1.40
Water content at field capacity (cm^{3}cm^{-3})	28.8	29.7	29.0	14.4	27.2

N,1°29E), southwestern France, a clay loam soil and a semi-continental climate (Table 1).

Four spreading techniques were simulated: band spreading, broadcast spreading, incorporation of slurry after surface application and direct injection of slurry at 5- and 10-cm depths (Table 2). Volt'Air uses data from Thompson et al. (1990) who consider that a dose of 60 m^3 of slurry is needed to cover an area of 1 ha. For a dose of 30 m^3 ha^{-1}, only 50 % of the field area is thus covered with slurry. Bands of slurry were assumed to have a width of 10 cm and be spaced by 30 cm. Injection slots were assumed to be triangular, with a base of 2.5 cm and spaced by 25 cm; the slot volumes are then 25 and 50 m^3 ha^{-1}, respectively.

To account for soil compaction, different sizes of slurry tankers were simulated. We also simulated an umbilical pipe system, requiring only a light tractor and no tanker. The capacity of the slurry tanker, the number of axles and wheels, the inflation pressure, the type of spreading device, the working width, and the power of tractor are mutually related. We simulated a load on the tanker wheel of 3.65 Mg for a 6-m^3 tanker and a trafficked area covering 7 % of the field. Simulated wheel load ranged between 4.5 and 5.3 Mg for 15 and 20-m^3 tankers, trafficking between 5 and 33 % of the field area, depending of the working width of the spreading device. Tractor wheels were also taken into account. The power of tractors required for spreading was 51 kW for umbilical spreading and for the 6-m^3 tanker, 100 kW for band spreading with the 15-m^3 tanker, 120 kW for the 20-m^3 tanker and for an injection device mounted on the 15-m^3 tanker, and 150 kW for the self propelled 15-m^3 tanker with extra-large tires.

2.2.2 Principle of the testing method

OSEEP simulated NH_3 and N_2O emissions, expressed in kg ha^{-1}. However, we have not conducted field trials to measure NH_3 and N_2O emissions against which OSEEP outputs could be compared. Hence, we reviewed papers reporting field measurements of NH_3 and N_2O emissions with various spreaders (Clemens et al. 1997; Dosch and Gutser 1996; Rodhe et al. 2006; Smith et al. 2000; Vandré et al. 1997; Weslien et al. 1998; Wulf et al. 2002a; Wulf et al. 2002b). Yet, the field trials reported in those papers were conducted in different conditions regarding soil, climate, and slurry type. Hence, the measured emissions of the reported field trials cannot be directly compared with the simulated emissions.

Table 2 Characteristics of the simulated spreading techniques for a 30-m^3 slurry application

	Delay before incorporation (hour)	Depth of incorporation (cm)	Part of slurry incorporated (%)	Field area covered by slurry (%)	Area of the field trafficked by wheels (%)				
					Size of slurry tanker (m^3)				
					0[a]	6	15	15[b]	20
Broadcast spreading	–	–	–	50	7	7	10	–	11
Band spreading	–	–	–	33	7	–	5	17	5
Incorporation	1	8	80[c]	33	14	–	14	–	14
Injection	–	5	83	20	–	–	20	50	22
	–	10	100	10	–	–	30	67	33

[a] Umbilical spreading (no tanker)

[b] Self-propelled tanker with extra-large tires

[c] Estimate for incorporation with a harrow

Conversely, we could not reproduce in OSEEP the conditions under which those trials were conducted. Indeed, OSEEP uses many input data, among which hourly and daily weather data, which were not described in these papers. Therefore, we compared simulated and measured emissions on a relative basis. We used relative emission factors, defined as the ratio of N emissions from one spreader to N emissions from a reference spreader during the same trial. For example, OSEEP predicted 29.6 and 11.6 kg ha^{-1} N-NH_3, respectively, for band spreading and injection at 5-cm depth for a 20-m^3 tanker on the Kerlavic site in 2002. In these conditions, the relative emission factor for injection with respect to band spreading is 39 %. We calculated relative emissions factors with OSEEP outputs for all spreaders in the 35 combinations of sites and years described in "section 2.2.1". We also calculated relative emission factors with the measured emissions reported in the eight publications cited above in this section. For all relative emission factors, the selected reference technique was band spreading because band spreading was the most common technique tested in field experiments. The distributions of experimental and simulated relative emission factors were subsequently compared.

3 Results and discussion

3.1 Testing of the OSEEP model

We used the nonparametric statistical test of Wilcoxon-Mann-Whitney, which assesses the similarity of two populations. The ranges of relative NH_3 and N_2O emission factors from field measurements and from OSEEP outputs were found similar for the three application techniques ($p<0.05$) (Fig. 3). For NH_3, the slightly larger range obtained with the experimental values may be explained by the more diverse conditions under which field emissions were measured, as compared to the simulated emissions. For N_2O, the simulated emissions are higher with the injection technique. This overestimation may be due to the constant N_2O:N_2 ratio in STICS, whereas this ratio is expected to decrease with increasing anoxic conditions (Bessou et al. 2010). Interestingly, the relative emission factors for injection are either below or above 100 %: the injection of slurry could lead to either a decrease or an increase in N_2O emission, as compared to band spreading. The same behavior was also reported before (Langevin et al. 2010; Velthof et al. 2003). This result is discussed further in

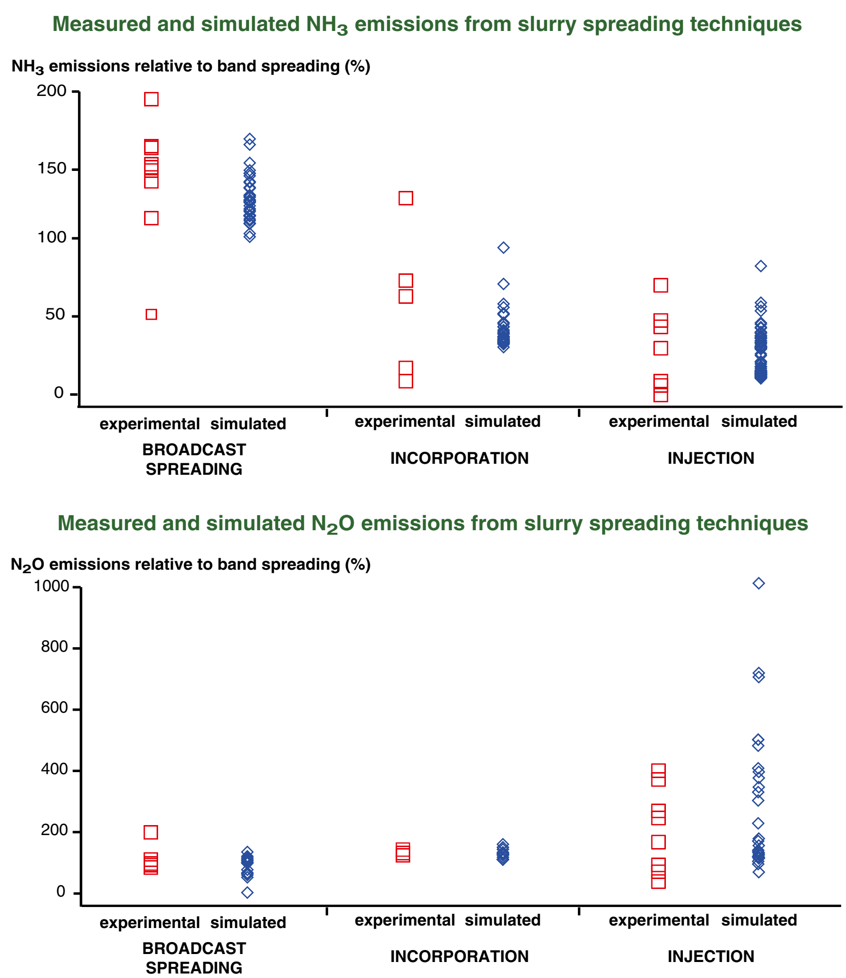

Fig. 3 Comparison of NH_3 and N_2O relative emission factor calculated with simulated and measured emissions. Each data point represents the ratio of N emissions from one spreading technique to N emissions from a reference technique during the same trial, as reported in the literature or simulated with OSEEP. Experimental and simulated distribution of NH_3 and N_2O relative factors were found similar ($p<0.05$) for the three spreading techniques. Note that overlapping dots appear bolder

"section 3.2.3". Experimental conditions relative to the soil, weather, and slurry type were more diversified in the literature than in the simulations. Yet, a large part of the range of the NH_3 and N_2O relative emission factors was reproduced with the simulated data, showing that OSEEP performs relatively well and is valid for a wide range of soil, weather, and slurry conditions.

3.2 Examples of OSEEP uses

The global effect of slurry spreaders of various sizes and using different spreading devices can be simulated by combining the three elementary effects of slurry incorporation, slurry spatial distribution, and soil compaction. We show below how OSEEP can be used to assess the environmental impact of slurry spreaders to help the eco-design of future spreaders. We simulated four examples, which are detailed in Langevin (2010). Note that professional operators in the field of manure application consider that the main criteria for the design of their spreaders are, in decreasing importance, the compliance with the applied dose, the homogeneity of spreading, the preservation of the soil fertility and trafficability, and to a lesser extent, the working rate (Thirion and Chabot 2003).

3.2.1 Homogeneity of application

Homogeneity of application is evaluated with the coefficient of variation (CV) of the distribution of the amount of slurry applied in the field. Thanks to the great improvements achieved during the 1990s, CVs of the worst spreaders are about 50 %, while spreaders with CV <30 % are now considered satisfactory (Thirion and Chabot 2003). OSEEP showed that the impact on NH_3 and N_2O was not significant within the range of spatial distributions achieved by current broadcast spreaders, i.e., with a CV lower than 50 %. Indeed, when spread evenly, i.e., with CV=0 %, NH_3 and N_2O emissions did not differ by more than 5 % from broadcast spreading with CV=50 %. As professional operators view homogeneity of application as a priority, more field research would be needed to confirm our result.

3.2.2 Using light and heavy equipment

We evaluated the impact of using light and heavy equipment for slurry spreading, taking into account both the impact on the soil bulk density and the area of compacted soil. We found that the spreader size had no significant impact on NH_3 emissions. The benefit of lighter machines was relatively moderate in relation to N_2O emissions (Fig. 4), with a median reduction of 5–10 % as compared to a 15-m^3 tanker trailed by a tractor. However, we found a significant increase of N_2O emissions for a heavy self-propelled 15-m^3 tanker with three extra large tires, intended to distribute the stresses over a larger contact surface area. The wheel load and tracks cover reached 8.5 Mg $wheel^{-1}$, trafficking up to 67 % of the field, which led to increased N_2O emission by 20 %. This indicates that more research is needed to optimize trade-offs between the floatation of spreaders and their impact on soil compaction and induced N_2O emissions.

3.2.3 Slurry injection

Slurry injection is an efficient mean to reduce NH_3 emissions, but entails to a possible increase of N_2O emissions by concentrating moisture and nitrogen in the injection slots. Langevin et al. (2010) found opposite effects of injection on N_2O emissions in the literature. Opposite effects were also obtained using OSEEP: simulations showed systematic increases of N_2O emissions for slurry injection with respect to surface spreading, excepted on the Kerlavic site in 2007. For an injection at 5-cm depth, N_2O emissions were increased by respectively 30 and 36 % with respect to band spreading and broadcast spreading. Conversely, the N_2O emission of injected slurry on the Kerlavic site in 2007 was reduced by 20–38 % depending on the injection depth as compared to broadcast spreading. On the Kerlavic site in 2007, the soil was almost saturated by water. For this reason, the effect of nitrate content on denitrification became predominant as compared to that of the water content. The effect of nitrate content decreases with increasing nitrate concentration following a Michaelis-Menten function (Bessou et al. 2010; Hénault and

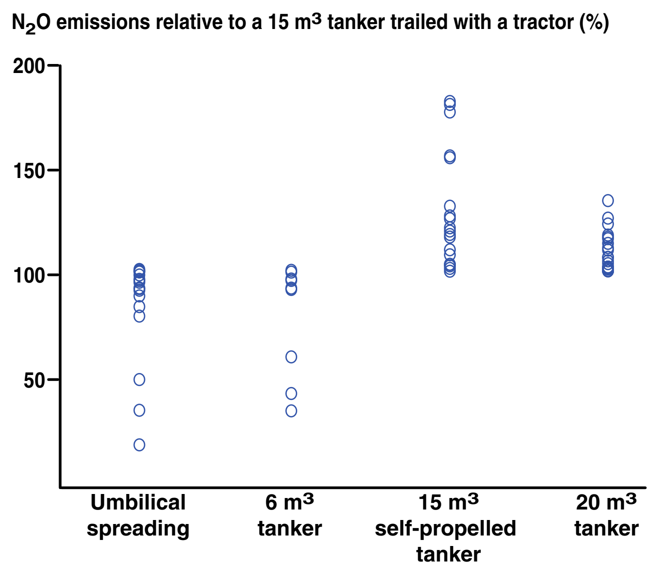

Fig. 4 Effect of the size of slurry tanker on N_2O emission. All spreaders are trailed with a tractor, except the 15-m^3 self-propelled spreader; umbilical spreading is achieved with a tractor only. Each dot represents simulated N_2O emissions from a spreader relative to the N_2O emissions from a 15-m^3 tanker trailed with a tractor during the same trial. While the benefit of lighter machines appears interesting in some conditions, the use of heavy self-propelled spreader may considerably increase N_2O emissions. Note that overlapping dots appear bolder

Germon 2000). Consequently, when averaged over the whole field area, the same amount of slurry distributed over 1 ha led to higher N_2O emissions than when it was concentrated in the injection slots. Therefore, if the slurry is spread before a rainy period and soil saturation by water, injection of this slurry may limit both NH_3 and N_2O emissions as compared to broadcast spreading.

3.2.4 Injection depth

Injection depth has an effect on NH_3 and N_2O emissions, as it determines the amount of slurry injected, which in turn determines the proportion of slurry exposed to air, as well as local concentrations of moisture and nitrogen. We calculated that slurry injected at depths of 2.5, 5, and 10 cm corresponded to a proportion of injected slurry of 42, 83, and 100 %, respectively. The effect of injection depth was much more pronounced on NH_3 than on N_2O emissions. Considering all sites and years, the median NH_3 emission decreased by 40, 69, and 90 % when injected respectively at 2.5-, 5-, and 10-cm depths as compared to band spreading. Conversely, when injection led to higher N_2O emissions, that is, excluding Kerlavic in 2007, the median N_2O emission increased by 30 % for both 2.5- and 5-cm injection depths, and by 73 % for 10-cm depth. As a deeper injection also requires a higher draught force (Hansen et al. 2003), an injection depth of 5 cm can be considered as a good trade-off between NH_3 and N_2O emissions. However, Webb et al. (2010) took also into account the indirect emissions of N_2O caused by the redeposition of NH_3 onto land (IPCC 2006). They found that the total emissions of N_2O will not increase when limiting NH_3 emissions, if the direct emissions of N_2O increase by less than 35 %. Moreover, Velthof et al. (2003) stated that injection at 10-cm depth might lessen N_2O emissions as compared to an injection at 5-cm depth, because a longer diffusion path would increase the chance that N_2O is reduced to N_2. As OSEEP can overestimate N_2O emissions for deep injection, the inclusion of a better modeling of the $N_2O{:}N_2$ ratio for denitrification is needed to investigate further the question.

3.3 Generalization of the modeling and testing approach

The approach can be generalized to other farming practices. The following steps present the generic modeling approach used to simulate the effects of one farming practice on environmental or agronomic variables at the field scale. Both types of variables are referred to as agro-environmental variables.

(1) Identification of all possible effects of the farming practice affecting the emission mechanisms of agro-environmental variables. A literature review is performed to gain an understanding of the mechanisms governing the agro-environmental variables and their main controlling factors. The extent to which a farming practice affects agro-environmental variables can be assessed from field trials reported in the literature. All possible interacting effects of the practice are subsequently listed.

(2) Selection of the main potential effects on emissions for their inclusion in a modeling approach. Farming practices affect the agro-environmental variables to various extents. The effects of the studied farming practice are ranked according to their influence on the studied agro-environmental variables.

(3) Selection of candidate models aiming at the simulation of significant effects of the studied farming practice. Models that simulate the effects identified in step 2 are reviewed. If there is no comprehensive model able to simulate all the desired effects, several models must be selected and integrated. A main model is selected, usually a crop model, to which additional models will be subsequently linked. To account for one effect ignored by the main model, e.g., soil compaction, the modification of some of its input variables and/or parameters is investigated. These input variables/parameters should be standard data, predictable with other models.

The choice of models depends on several criteria: the effects to be simulated, the availability of data to feed the models, their time-step, and their domain of validity. The linkage of models with different time-steps is not problematic because the models are run successively, with no feedback between them. OSEEP, for example, integrates STICS and Volt'Air, which time-steps are 1 day and 1 h, respectively. This absence of feedback between models limits the risk of discrepancies due the amplification of uncertainties generated by the models (Gabrielle et al. 2006). Regarding the domain of validity of models, priority should be given to generic models that are valid under a wide range of conditions. In this regard, mechanistic models have a greater capacity of extrapolation as compared to empirical models, only valid under their calibration conditions. Linking empirical and mechanistic models is not problematic: mechanistic models often include empirical functions. Indeed, a detailed description of several levels of hierarchy in models often leads to errors (Sinclair and Seligman 2000). The main issue when using empirical models is the restriction of use to the range of conditions over which empirical model were calibrated.

(4) Validation issues. Although each model has been validated independently with measured data, it is

deemed important to check the performance of the integrated model. However, the high costs of field experiments can be a major limitation to perform classical tests and to compare observed and simulated data. If such experiments cannot be carried out and if no complete dataset is available to test the integrated model, we propose a testing method that assesses model outputs a relative basis. The output results, e.g., a polluting emission in the environment, are expressed as a multiplicative factor of the emission caused by a reference practice in the same conditions. This ratio is a relative emission factor, specific for each emission of each studied practice. Relative emission factor calculated with model outputs can be compared with relative emission factor calculated with field measurements from the literature. The interactions between the farming practice and the soil and climate conditions are reflected in the relative emission factors. A wide range of values for one relative emission factor indicates either a large variability of the farming practice itself such as several depths for slurry injection, and/or strong interactions with the soil and climate conditions. A great advantage of models is that they can single out the effect of agricultural practices and identify the conditions when they are advisable or not.

Although based on existing models, our approach requires a significant knowledge of the biological, chemical, and physical processes into play. This knowledge must be used in order to (1) identify the possible effects of the studied farming practice on agro-environmental variables and (2) to determine which models would be the most appropriate for the simulations. Sometimes, effects of farming practices may be poorly understood, such as tillage management on N_2O emissions (Soane et al. 2012). In this case, our approach might not be possible, or might result in a model with a poor predictive capacity. However, models are improved as knowledge advances. Future improvements in any of the linked model will be easy to implement in the integrated model, such as a better modeling of the N_2O:N_2 ratio in STICS (Bessou et al. 2010). Conversely, integrating models may offer insights to improve the initial models. For instance, the importance of the issue of soil quality when building OSEEP warrants future research to include soil compaction in agro-environmental models like STICS.

This approach in which models are integrated and tested is useful to perform low cost prospective studies when no or little data is available. This approach makes it possible to go ahead with new supported hypotheses despite time and budget limitations that hinder in-depth investigations.

4 Conclusion

We elaborated a comprehensive simulation model called OSEEP, predicting NH_3 and NO_2 emissions from slurry spreading. OSEEP was able to reproduce a large range of the NH_3 and N_2O relative emission factors calculated from field measurements reported in the literature. We show that the improvement of the spatial distribution achieved by current spreaders, i.e., with a coefficient of variation lower than 50 %, has little impact on NH_3 and N_2O emissions. We also show that the use of heavy spreaders, trafficking a large part of the field area, may lead to an important increase of N_2O emissions. We simulated systematic decreases in NH_3 emission and increases in N_2O emissions for slurry injection with respect to broadcast spreading, except in one case. When the water saturates the soil porosity, injection of this slurry may limit both NH_3 and N_2O emissions as compared to broadcast spreading. We show that slurry injection at 5-cm depth limits NH_3 emissions while mitigating the increase of N_2O emissions. However, the inclusion of a better modeling of the N_2O:N_2 ratio in OSEEP would lead to a more accurate assessment of trade-offs between NH_3 and N_2O emissions at various depths of injection. The modeling and testing methods proposed can be generalized to other farming practices. Our approach makes it possible to conduct low cost prospective studies on the impacts of farming practices when no or little data is available.

Acknowledgments We are very grateful to L. Garcia for his help with Volt'Air simulations. We also thank V. Parnaudeau, B. Mary, N. Beaudoin, M. Launay, and the late N. Brisson for their advices with STICS, as well as S. Guillaume, O. Naud, C. Tinet, and B. Gabrielle for their expertise on modeling and programming issues, and P. Roux for his support and advice. This work was part of the research project "ECODEFI" (ecodesign of spreading equipment) and was financially supported by ADEME.

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