Simulating the management of wastes at a territory level in the peri-urban market gardening systems of Dakar (Senegal): the case of the Rufisque department

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Abstract
In the Rufisque department in Senegal, the regular supply of farmers with organic residuary products (ORP), namely livestock wastes, is a major constraint. The Magma model has been used to assess the supply of farms with ORPs. Comparing a base scenario, reflecting the actual farmers' practices, with two alternatives where practices and means of transportation are better adapted, the simulations have shown a more even application of ORPs to crops, the decrease of the nitrogen leaching risk and the reduction of the total transport mileage, namely when crop farms are relocated in a remote rural area.

Introduction

According to United Nations forecasts, the people living in cities will double within the 1995-2025 period passing from 2.8 to 5.3 billions inhabitants, 90% of this growth occurring in developing countries [1]. This quick urbanization is challenging with respect to preservation of the environment and food supply [2]. In the Dakar (Senegal) suburbs, the market-gardeners of the Rufisque department (about 250 farmers covering 590 ha), confronted to the lack of irrigation water, exhibit a strong demand in ORPs of adapted quality and quantity. These ORPs have two main functions: supplying nutrients to crops and maintaining the soil humidity (mulch effect). However, actual practices lead to fertilization excesses in some farms. Moreover, all required ORPs, namely animal manures, are not always available to farmers. In fact, the available ORP production is only 145 tN/year in the district, i.e. much below the demand of 220 tN/year as estimated by farm surveys. The complexity of the ORP supply chain and the diversity of market-gardening practices and soil conditions call for the use of simulation modeling to better understand the interactions between the numerous ORP producers and consumers. This paper's aim is to show the benefit of using a flow-stock dynamical model to assess management scenarios of ORPs on a whole-territory scale. Successive simulations allow one to devise better strategies of ORP uses on market-gardening in the Rufisque district while limiting the risk of nitrogen pollution.

Material and methods

Data used

Farm surveys have been done in the Rufisque market-gardening territory: (1) on animal farms, to know the types of animals, the size of herds and the uses of the ORPs they produce; (2) on the ORP transporters (mainly carters), to know the payloads and transportation times; (3) on crop farms using ORPs, to know the cultivation systems: soil, hydromorphy, crop sequences, yields, fertilization (ORP doses and schedules) and irrigation practices. The main characteristics of soils (humidity, C-N contents, apparent density) and ORPs (DM, C-N contents) have been determined according to standard methods at the Laboratory of Analytical Means (LAMA, IRD, Dakar). Nitrogen apparent utilization coefficients (AUC) of chemical fertilizers and ORPs, as well as crop requirements, have been taken from the literature [3,4]. The rate of nitrogen mineralized in soils has been calculated based on an average 1.3 % y^{-1} coefficient given by experts. These values are in Table 1.

Table 1. Characteristics of ORPs, crops and soils in the market-gardening area of Rufisque (Senegal)

Organic residual product	Horse manure	Cattle manure	Slaughter house waste	Poultry manure	Hens dropping	Fish meal	Peanut dust
Number of units	1605	862	55	183975	10000	4	2
TN produced (kg y^{-1} U^{-1})	16	24	18	0.4	0.48	2738	277
DM content (% ww)	80	80	68	85	78	92	85
TN content (% ww)	1.44	1.28	1.22	3.18	5.07	3.54	0.76
AUC (%)	12	12	36	12	36	36	6
CROPS	Green cabbage	Carrot	Lettuce	Pepper	Tomato		
Average yield (t ha^{-1})	35	41	37	38	40		
N needs (kg ha^{-1})	123	144	93	156	140		
SOILS	Dek-Dior	Bane-Kew	Kew	Dek	Bane		
TN (g kg^{-1} dry soil)	0.9	1.6	2	1.3	1.2		
Apparent density (t m^{-3})	1.3	1.5	1.5	1.5	1.5		
Mineralized N (kg ha^{-1} y^{-1})	38	78	98	63	59		

DM, dry matter; TN, total nitrogen; ww, wet weight; AUC, apparent use coefficient; humidity and depth were fixed at 20% and 0.25 m for all soils.

Model description

The Magma simulation model [5] allowed us to represent the agricultural recycling system of ORPs in Rufisque as sets of production (PU) and consumption units (CU) linked by possible transfers of ORPs from the PUs to the CUs by transportation means. Taking as input parameters the characteristics of the PUs, CUs, transportation means and management rules, Magma allowed us to simulate the time evolution of the PUs and CUs stocks, ORP transport and application activities, along with agronomical, logistical or environmental indicators (see below). To account for the Rufisque territory in the simulations, 183 ORP producers have been merged into 16 PUs according to their production type, size and location (Fig. 1) of which: 3 PUs produce horse manure, 4 cattle manure, 5 poultry manure, 1 hens droppings, 1 slaughter-house waste, 1 fish meal and 1 peanut dust. Similarly, 250 market-gardening farms have been merged into 17 CUs according to their production, location, soil, and other characteristics like hydromorphy. The number of real farm per CU varies between 2 and 63. The ORP transfer flows are dependent upon the links established between the PUs and the CUs (adequacy of application of PU's ORPs to CU's crops) and transportation means.

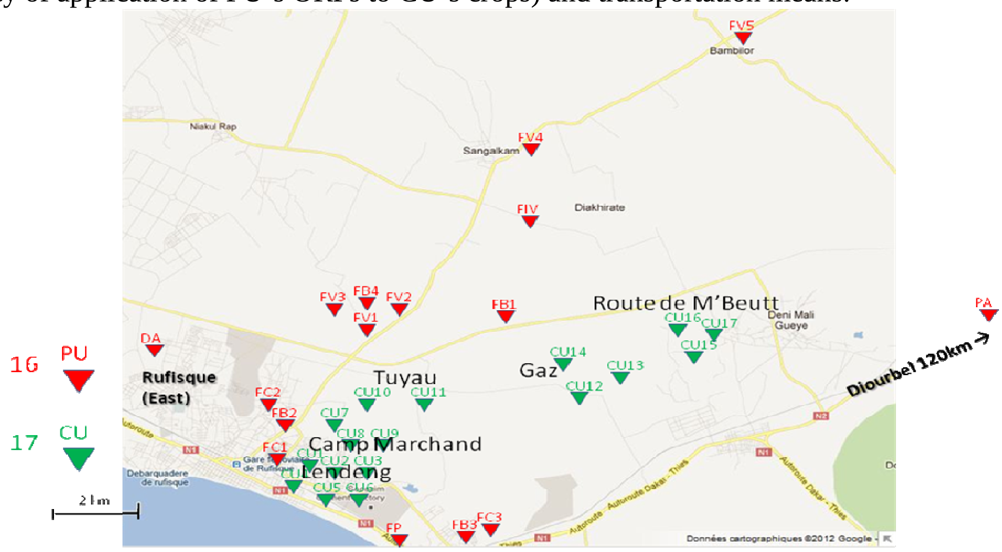

Figure 1. Locations of ORP production and consumption units in the Rufisque territory.

Agronomical and environmental assessment

To assess the performances of ORP territorial management, various indicators have been calculated: environmental (excesses of ORP production at the PU's, of nitrogen balance at the UC's), agronomical (amounts of ORP applied on crops, crop requirements satisfaction, use of chemical fertilizers) and logistical (accumulated transport times, mileage travelled).

The excess of N balance (kg N ha^{-1} y^{-1}), that can be interpreted as leaching risk, is given by Eq. (1):

$$NB = N_{soil} + N_{min} \; x \; AUC_{min} + N_{pro} \; x \; AUC_{pro} - N_{abss} \quad (1)$$

with, NB, the nitrogen balance, N_{soil}, mineralized soil N (see Table 1), N_{min}, N in mineral fertilizers, N_{pro}, N in ORPs, AUC_{min}, the apparent utilization coefficient of mineral fertilizers (=0.6), AUC_{pro}, the apparent ORP utilization coefficient (see Table 1), N_{abs}, N uptake by plants (see Table 1).

Scenario analyses

The assessment of the three following scenarios are presented hereafter:

- S0: base scenario; it has been calibrated by successive simulations to approach the reality. It is characterized by farmer actual practices (i.e. massive application of ORPs on crops as mulch) and by numerous horse-carts which are the most popular means of ORP transportation.
- S1: scenario derived from S0 with adjustment of organic fertilization practices to reduce the risk of nitrogen excess observed with the actual ones (i.e. selective decreasing application doses of 12% on average: 351 vs 378 kg N_{ORPs} ha^{-1}, in S1 and S0 respectively)
- S2: scenario derived from S1, with relocation of UCs #12-17 60 km away of the actual market-gardening area to anticipate the lack of irrigation water and adaptation of the ORPs means of transportation to the new distances to travel (i.e. trucks substituted for carts).

Results and discussion

With respect to the crop demands corresponding to actual practices, some UCs show in simulation of S0 (Fig. 2) a lack of ORP supply (application rate <<100% for UCs #1, 4, 7, 8, 10, 11). However, taking into account the applied N from mineral fertilizers, the nitrogen balance in S0 (Table 2) shows an excessive N fertilization on small farms (UCs #1-3 and 6-9) whereas others UCs exhibit a deficit (UCs #10-14).

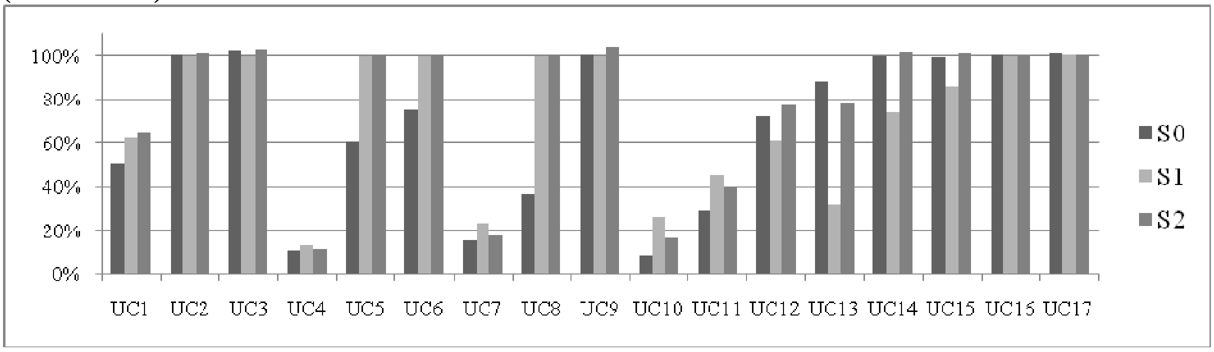

Figure 2. Application rates of ORPs with respect to the ORP demand specified by the UCs, in the 3 scenarios.

Simulation of S1 shows that some UC previously overfertilized in S0 (UCs # 2, 3, 6, 9) released ORPs for the benefit of UCs with former deficit (UCs #1, 5-8, 10, 11). In contrast, remotely located UCs like UCs #12-15 are less supplied than before (Fig. 2). In S1 the mean N balance has improved (23 *vs* 27 kgN$ha^{-1}$$y^{-1}$, see Table 2); hence, the risk of N leaching is assumed to be lower.

Simulation of S2, with the same crop demands as in S1, does not change much the N balance. However, some of the UCs relocated out of town (#12-15) are better supplied with ORPs (Fig. 2) and their N balance is slightly improved (Table 2).

Table 2. Fertilization and nitrogen balance of the CUs for scenarios S0, S1 and S2

	Number of farms	Surf	Mineral fertilizers	Organic fertilizers			Nitrogen balance (NB)		
		ha	kg N $ha^{-1}y^{-1}$						
				S0	S1	S2	S0	S1	S2
UC1	6	5	353	441	537	561	334	343	368
UC2	4	4	518	1266	630	637	487	406	407
UC3	3	2	420	1100	540	556	327	260	262
UC4	22	24	352	92	114	99	28	31	29
UC5	12	11	517	761	630	633	50	19	35
UC6	3	5	420	812	540	543	317	284	285
UC7	20	20	504	180	278	211	160	158	168
UC8	18	19	750	534	729	730	178	192	190
UC9	2	1	370	1303	648	673	369	290	293
UC10	35	105	235	5	16	10	-105	-103	-103
UC11	15	45	45	64	100	88	-27	-26	-18
UC12	3	20	188	325	274	349	-85	-91	
UC13	23	64	236	247	89	220	9	-14	5
UC14	3	5	188	451	333	458	-49	-63	-48
UC15	6	16	236	278	240	283	61	47	63
UC16	63	190	235	281	281	281	62	61	62
UC17	16	47	235	284	281	282	62	62	62
Mean			260	237	224	235	27	23	27
Total	254	582	151320*	137934*	130368*	136770*	15661*	13269*	15805*

* in kg N y^{-1}

For most UCs, it would be further possible to set up mineral fertilizer applications so that UCs' Nitrogen balance tends towards 0 whereas it is of 27, 23, 27 kg N ha^{-1} y^{-1} for S0, S1 and S2 respectively (Table 2). This would reduce the average application rate of chemical fertilizers to 222, 227, 220 kg N ha^{-1} y^{-1} for S0, S1 and S2, to be compared with the current 260 kg ha^{-1} y^{-1} (Table 2). It will also save 22, 19 and 23 t N y^{-1} as fertilizers on the territory.

Because the means of transportation are numerous enough and the ORP demand exceeds the local offer (220 *vs* 145 t N), non-used ORP excesses are low in the 3 scenarios: 5, 12 and 7 t N y^{-1} corresponding to 4, 8 and 5% of ORP N production for S0, S1 and S2 respectively. In S1, the decrease in overfertilization led to an increase in the non-used excess of ORP compared with S0, while in S2, the better efficiency of ORP transportation (trucks *vs* carts) led to the same overfertilization and to similar non-used ORP than S0.

The traveled mileage by ORP transportation means is decreased by 16% between S0 (194800 km) to S1 (163500) and then by 70% between S1 and S2 (49222 km). In the first case, there is a more even repartition of ORPs over the territory. In the second case, the substitution of trucks for numerous carts led to a more efficient transport (higher payload), diminishing the total mileage, even distances where increased between the relocated UCs and the UPs.

Conclusion and perspectives

Using the Magma model allowed us to better understand and characterize the constraints the UCs must satisfy to be delivered with ORPs at the whole territory level. The dynamical nature of the model (although not demonstrated in this paper) also helps identify and quantify the management events occurring over time.

Compared with S0, scenarios S1 and S2, by adjusting the fertilization rate to better practices lead to a more even distribution of ORPs among the UCs, a decrease in the Nitrogen balance excess and a reduced traveled mileage due to an increase of transport efficiency (namely in S2 where trucks are substituted for horse-carts). Environmental risks, namely N leaching are thus reduced in S1 and S2 as well as, possibly, chemical fertilizer application to crops. Using the nitrogen balance in the current study as an N leaching risk indicator, although seemingly relevant in irrigated agriculture on sandy soils, may have some limits. In fact, other parameters of possible N losses (volatilization emission, ORPs’ N equivalence coefficient) have not been measured but estimated from the data found in the literature. Refining the indicators used to better assess agronomically and environmentally such simulated management scenarios of ORP recycling is a perspective.

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