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Abstract

The change in nitrogen balance causes many environmental and socioeconomic impacts. In relation to food production and nitrogen release in wastewater systems, wastewater and sludge discharge and mineral fertilizer use intensify nitrogen imbalance of a region. The replacement of mineral fertilizer by nitrogen from treated wastewater, biosolids, and treated urine is a promising alternative. This work presents a model to support decision taking for the management of reactive nitrogen flows in wastewater systems based on system dynamics. Six scenarios were simulated for nitrogen flows in wastewater systems and related components.

Keywords separated by ' - '

Reactive nitrogen - Sustainable sanitation - System dynamics - Urine segregation

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RESEARCH ARTICLE

Decision support system for management of reactive nitrogen flows in wastewater system

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Abstract
The change in nitrogen balance causes many environmental and socioeconomic impacts. In relation to food production and nitrogen release in wastewater systems, wastewater and sludge discharge and mineral fertilizer use intensify nitrogen imbalance of a region. The replacement of mineral fertilizer by nitrogen from treated wastewater, biosolids, and treated urine is a promising alternative. This work presents a model to support decision taking for the management of reactive nitrogen flows in wastewater systems based on system dynamics. Six scenarios were simulated for nitrogen flows in wastewater systems and related components.

Keywords Reactive nitrogen · Sustainable sanitation · System dynamics · Urine segregation

Introduction

The anthropogenic fixation of reactive nitrogen, mainly used in agriculture for food production, has caused many changes in society, economy, and environment. As regards the social issue, estimates indicated that about half of the global population would not have sufficient food without use of nitrogen fertilizers in food production system (Erisman et al. 2008; Erisman et al. 2015).

As regards the economic issue, an important aspect to be emphasized is the global energy consumption to produce nitrogen fertilizer. The nitrogen fertilizer industry consumes about 2% of world energy (Sutton et al. 2013). On average, the production of 1 t of ammonia demand about 36.7 GJ if based on natural gas and 45 GJ if based on coal, oil, and naphtha (IFA 2009). Due to this fact, the food prices are strongly influenced by the energy prices.

From an environmental point of view, transformation of inert nitrogen to its reactive forms by industrial fixation (both ammonia and energy production) and intentional biological nitrogen fixation in agriculture has exceeded the planetary boundary for biogeochemical nitrogen cycle as indicated by Rockstrom et al. (2009) and Steffen et al. (2015).

Sutton et al. (2013) presented that these anthropogenic activities produce at least 200 Tg N (teragram nitrogen) per year. It is more than three times the planetary boundary proposed by Steffen et al. (2015), of 62 Tg N per year. Nitrogen fertilizer represents 60% (120 Tg N) of produced anthropogenic reactive nitrogen (Sutton et al. 2013), of which, around 50% is released to the environment due to low use efficiency (Smil 2011).

To mitigate the alterations of the biogeochemical nitrogen cycle is necessary to minimize the conversion of inert nitrogen (N_2) to reactive nitrogen forms through drastic measures intended to close the cycle. This points directly to the optimization of existing reactive nitrogen flows management to meet the nitrogen demand mainly by mineral nitrogen fertilizer. The

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existing reactive nitrogen flow in sanitation system mainly by human excretion was set in 19 Tg N per year (Billen et al. 2013), which represents around 10% of anthropogenic reactive nitrogen production and 15% of nitrogen fertilizer production.

Conventional sanitation is characterized by open flows of water and nutrients, which does not focus adequately on important issues such as energy use in mineral fertilizer production, water supply and wastewater treatment, chemicals use in water and wastewater treatment, potable water use in non-potable uses such as for flushing toilets, and nutrients emissions to ecosystems. In this way, alternative more efficient means have been developed by the sustainable sanitation concept, where segregation and use of resources flows are designed to close the nutrients and water cycles linking sanitation systems and agricultural production. Additionally to macronutrients recycling, micronutrients can also be recovered as an additional advantage (Santos et al. 2015).

In relation to nitrogen recycling, urine segregation has shown to be an effective way for closing the cycle. Human urine contributes 80% of nitrogen load in wastewater flow (Munch and Winker 2011; Spangberg et al. 2014). The annual urine production per capita can fertilize 300–400 m^2, considering the nitrogen application rate between 50 and 100 kg N ha^{-1} (Richert et al. 2010). This means that about 34 people can fertilize 1 ha.

Reactive nitrogen management involves industry, agriculture, society, sanitation, and other sectors, forming a complex system. There is need for a holistic integrated approach about nitrogen management. The main objective of this study was to develop a model of decision support system for reactive nitrogen flows management in wastewater system.

Material and methods

The five steps of the modeling process developed by Sterman (2000) were used as methodology to develop the model. In the first step, "problem articulation," the problems of inefficient management of reactive nitrogen and its complexity was presented. The key variables that influence the amount of reactive nitrogen excreted and its use in agriculture considered in this study were population, animal, and vegetal protein consumption, and use efficiency of treated wastewater, treated urine, and biosolids in agriculture.

In the second step, the dynamic hypothesis are developed to explain the initial system behavior and its representation by causal loop diagrams of the conceptual model. Negative arrows (−) represent effects in the opposite directions and the positive arrows (+) represent effects in the same direction (Martín 2006).

In the third step, "formulation of simulation model," the stock and flow model is developed based on previous dynamic hypothesis. The causal loop and the stock and flow diagrams were developed using the software Vensim PLE Plus Version 6.3. The simulation was set for the period of 50 years, from the year 2000 to 2050.

The model was applied to a hypothetical region with 480,000 inhabitants in year 2000, characterized by agricultural production and inadequate sanitation as usual found in many in developing countries. In the "testing" and "policy design and evaluation" steps, simulations of six scenarios of policies for nitrogen flow management in wastewater system were carried out.

Decision support system for management of reactive nitrogen flows from wastewater system

Conceptual model

The dynamic hypothesis of this study was defined as follows:

> Nitrogen recycling from wastewater flows, including treated wastewater, treated urine and biosolids, can reduce the need for mineral fertilizer, reducing the conversion of inert nitrogen to reactive forms and, consequently, reducing reactive nitrogen emissions to ecosystems. Environmental and economical advantages will encourage more the nitrogen recycling.

The causal loop diagram formulated for the dynamic hypothesis is shown in Fig. 1. The system was divided in four parts, population, wastewater, urine segregation, and vegetal production subsystems. The population subsystem (in box 1) represents the variation of population size, protein consumption, considering type and amount, and human metabolism, in relation to nitrogen excretion. The wastewater subsystem (in box 2) represents the treatment and use of wastewater and biosolids as nitrogen sources for agriculture. The urine segregation subsystem (in box 3) represents the treatment and use of urine as nitrogen source for agriculture. The vegetal production subsystem (in box 4) represents the vegetal production, which depends on productivity and harvested area that demands nitrogen fertilizer.

Nitrogen discharged by wastewater from human excreta (*nitrogen in produced wastewater* variable) depend on population size and diet, which are influenced by lifestyle and income. An increase of *population*, *vegetal protein consumption*, and *animal protein consumption* produce an increase of *nitrogen in produced wastewater*. Digestibility rates of animal protein are generally higher than those of vegetal protein (WHO 2007). The higher the digestion and absorption of protein, more nitrogen will be excreted via urine. Due to digestibility values, an increase of *animal protein*

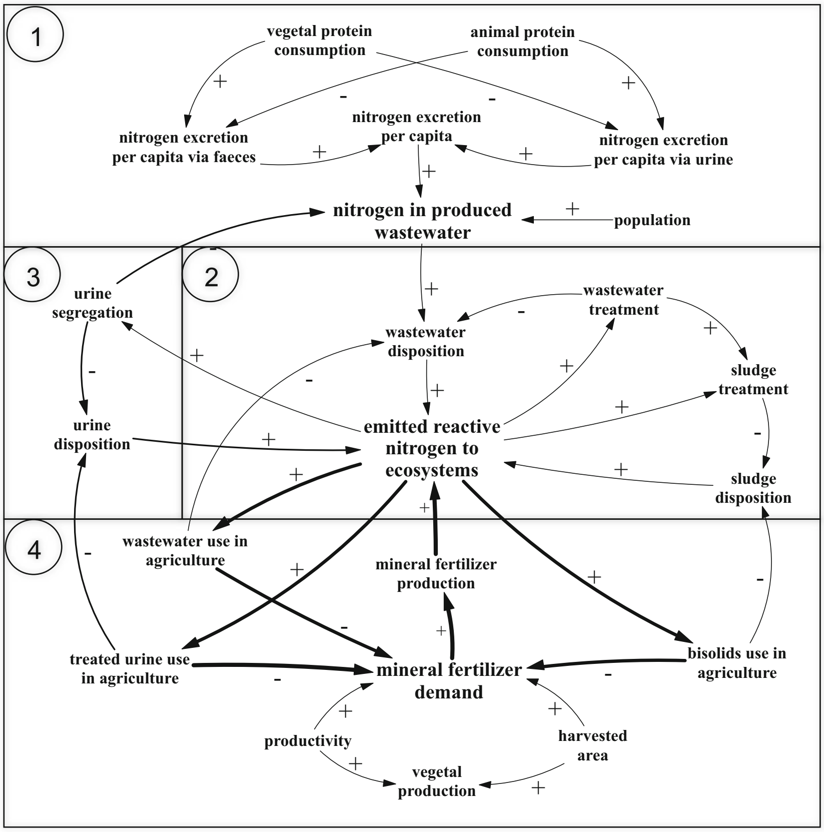


Fig. 1 Causal diagram of decision support system for management of reactive nitrogen flows in wastewater system

consumption variable causes an increase of *nitrogen excretion* per capita via *urine*. Note that, world consumption of animal products have significantly increased in recent decades (Westhoek et al. 2014). Particularly in some developing countries, growth of animal products consumption has been determined by economic and urban development (FAO 2009).

If *nitrogen in produced wastewater* is not collected, treated or recycled, it will be directly emitted to ecosystems (*wastewater disposition)* intensifying the nitrogen imbalance of the region already loaded by the application of mineral fertilizer in agriculture (*mineral fertilizer demand*). The higher the *vegetal production* caused by increase of *productivity* or *harvested area*, the higher the *mineral fertilizer demand*. A way to minimize the nitrogen inflow is to replace the *mineral fertilizer demand* in vegetal production system by *nitrogen in produced wastewater* in the form of treated wastewater, treated urine, and biosolids. Thus, a reduction of *emitted reactive nitrogen to ecosystems* in the region would be achieved.

Traditionally, treating and recycling resources from wastewater systems occur using treated wastewater for irrigation and biosolids for fertilization. However, irrigation and fertilization practices follow different logics. This alternative has some suboptimal aspects in terms of energy, water, and nutrients, which make the recycling system more expensive.

More efficient alternatives have been considered by the sustainable sanitation approach. *Urine segregation* has been shown to be a better alternative in relation to nitrogen use and recovery (Zhou et al. 2010; Larsen et al. 2009), due to the availability of concentrated nitrogen and the optimization of other resources as phosphorus (Mihelcic et al. 2011; Cordell et al. 2009).

It is expected that environmental impacts such as eutrophication, provoked by the *emitted reactive nitrogen to ecosystems*, together with rising prices of energy and fertilizers, cause a pressure for investments on new systems for nitrogen recycling. This is highlighted in Fig. 1 by thick arrows, representing links between three variables: *wastewater use in agriculture*, *treated urine use in agriculture*, and *biosolids use in agriculture*. This would cause a reduction of *mineral fertilizer demand*, and consequently a reduction of *mineral fertilizer production* and *emitted reactive nitrogen to ecosystems*.

Stock and flow model

The stock and flow models of population, wastewater, urine segregation, and vegetal production subsystems are here developed and detailed. The equations of the variables used are detailed in Appendix A.

Population subsystem

As described before, this subsystem includes the human metabolism and variation of population. The model to quantify the variation of *nitrogen in produced wastewater* is shown in Fig. 2. The *population* of the hypothetical region was determined by the logistic curve method, where *Ps* is the saturation population and, *K1* and *c* are coefficients.

Population, *nitrogen in gray water*, *nitrogen in water*, *nitrogen in yellow water*, and *nitrogen in brown water* determines the *nitrogen in produced wastewater*. Animal protein consumption per person per day (*animal protein* per capita *per day*), vegetal *protein* consumption per person per day (*vegetal protein* per capita *per day*), and protein digestibility rates determined nitrogen excretion via urine (*nitrogen in yellow water*) and nitrogen excretion via feces (*nitrogen in brown water*). The *total nitrogen excreted per year* in the hypothetical region was calculated by multiplying *nitrogen excreted* per capita *per year* and *population*. The *nitrogen excreted* per capita *per year* was estimated by sum of *nitrogen in yellow water* and *nitrogen in brown water*. The *urine segregation rate* was used to determine the nitrogen amount that enters the urine segregation subsystem.

Wastewater subsystem

Figure 3 shows the model representing nitrogen flows in the wastewater system. The produced wastewater is composed by yellow water (urine and water), brown water (feces and water), and gray water (kitchen and bathing water). The nitrogen amount that enters the wastewater system (*nitrogen in wastewater production*) was determined by *nitrogen in produced wastewater*, with the same meaning. The figure below describes the conventional wastewater system considered in this study.

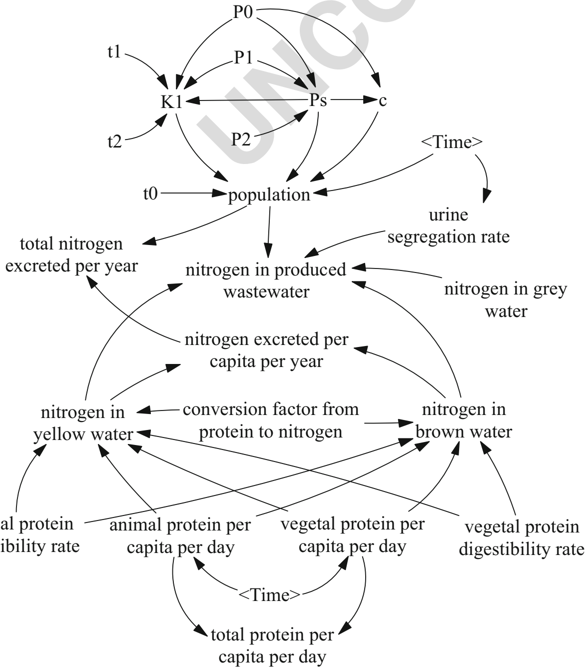


Fig. 2 Population subsystem

We assumed that part of *total nitrogen in produced wastewater* is diverted to the wastewater collection system. *Total nitrogen in collected wastewater* was determined based on the *wastewater collection rate*. The rest of *total nitrogen in produced wastewater* was assumed to be disposed into water ecosystems (*nitrogen discharged from produced wastewater*).

Part of *total nitrogen in collected wastewater* is treated and can be directed to wastewater recycling system. The *total nitrogen in treated wastewater* was calculated based on *wastewater treatment rate*. The other part of *total nitrogen in collected wastewater* was assumed to be disposed (*nitrogen discharged from collected wastewater*).

Part of *total nitrogen in treated wastewater* is recycled (*nitrogen in recycled wastewater*), which was determined based on *wastewater recycling rate*. The nitrogen emissions to ecosystems from wastewater treatment system, including sludge treatment system, occur by gases losses (N_2O, NH_3, NO_x, and N_2), non-recycled biosolids, and non-recycled treated wastewater.

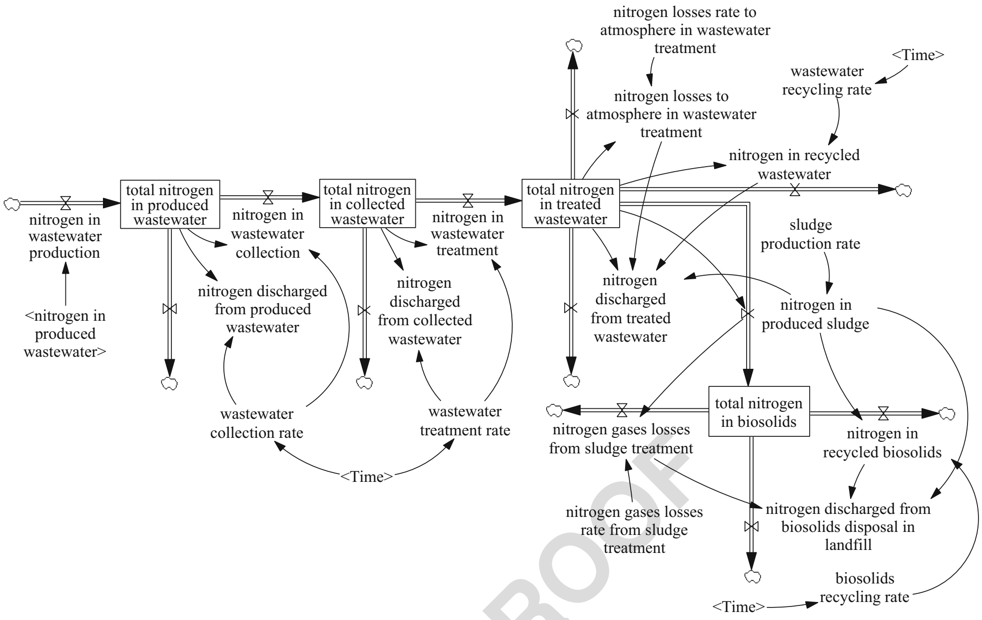
The *nitrogen discharged from treated wastewater* was obtained by subtraction between *total nitrogen in treated wastewater* and the sum of *nitrogen losses to atmosphere in wastewater treatment*, *nitrogen in produced sludge*, and *nitrogen in recycled wastewater*. In the view point of closing nitrogen cycle, *nitrogen discharged from treated wastewater* represents the potential available nitrogen in treated wastewater that could be used in agriculture, but that eventually is disposed into water ecosystems.

The *nitrogen in produced sludge* was estimated by *sludge production rate*, assuming that all produced sludge is treated. A part of *total nitrogen in biosolids* is recycled and the other part is disposed in landfill. The *nitrogen in recycled biosolids* was calculated based on *biosolids recycling rate*. The *nitrogen discharged from biosolids disposal in landfill* was obtained by subtraction between *nitrogen in produced sludge* and the sum of *nitrogen gases losses in sludge treatment* and *nitrogen in recycled biosolids*. The *nitrogen discharged from biosolids disposal in landfill* represents the potential available nitrogen in biosolids that could be used in agriculture, but that eventually is disposed.

Urine segregation subsystem

In Fig. 4 is shown the urine segregation subsystem model. *Urine segregation rate*, *nitrogen in yellow water*, and *population* determined the *total nitrogen in segregated urine*. Some nitrogen losses (*nitrogen losses to atmosphere in urine collection system*) occur before the urine treatment system, in

Fig. 3 Wastewater subsystem



the collection and segregation system, which were determined by the *nitrogen losses rate to atmosphere in urine collection system*. In urine treatment system also occur nitrogen gases losses, which were determined by the *nitrogen losses rate to atmosphere in urine treatment system*. The *nitrogen in recycled urine* was determined based on *urine segregation rate*, assuming that all treated and segregated urine is recycled.

Vegetal production subsystem

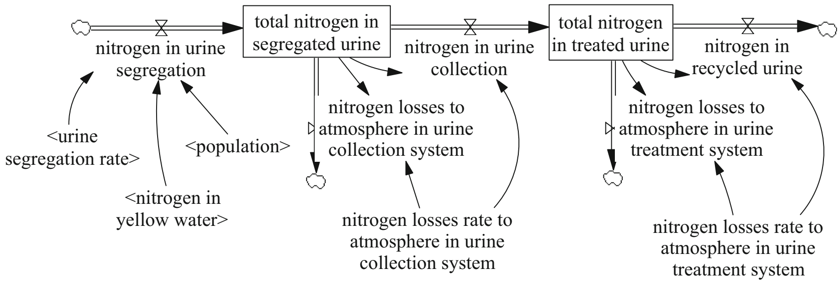
In Fig. 5 is shown the vegetal production subsystem model. The *vegetal production* was estimated through *harvested area* and *productivity*, which was related to the *desired nitrogen application rate from mineral fertilizer*. The *harvested area* varies in accordance to *growth rate of harvested area*. The *desired nitrogen application rate from mineral fertilizer* could be estimated based on crop production expectation, economic factors, or agricultural practices. The function WITH LOOKUP was used to determine the *productivity*, assuming that for given *desired nitrogen application rate from mineral fertilizer* exists an associated *productivity*.

The *total nitrogen application from mineral fertilizer* was obtained from *harvested area* and *nitrogen application rate from mineral fertilizer*, which was determined by the function IF THEN ELSE. Thus, if *nitrogen application rate from organic fertilizer* is equal to or greater than *desired nitrogen application rate from mineral fertilizer*, then *nitrogen application rate from mineral fertilizer* will be zero, if not, will be determined by the subtraction between *desired nitrogen application rate from mineral fertilizer* and *nitrogen application rate from organic fertilizer*.

The *nitrogen application rate from organic fertilizer* is the sum of equivalent nitrogen application from treated urine, treated wastewater, and biosolids. The equivalent nitrogen of each organic fertilizer was determined by multiplying the nitrogen application rate from each organic fertilizer by the nitrogen fertilizer replacement value (NFRV), which represents the fraction of applied total nitrogen by organic fertilizers that have the same effect in vegetal production that applied total nitrogen by mineral fertilizer (Schroder 2014).

The nitrogen losses by leaching, gases losses, and runoff of each organic fertilizer and mineral fertilizer were calculated to analyze the evolution of total nitrogen emissions (*emitted reactive nitrogen to ecosystems*) for different scenarios of nitrogen flows management. In order to analyze the potential environmental impact, the *emitted reactive nitrogen to*

Fig. 4 Urine segregation subsystem



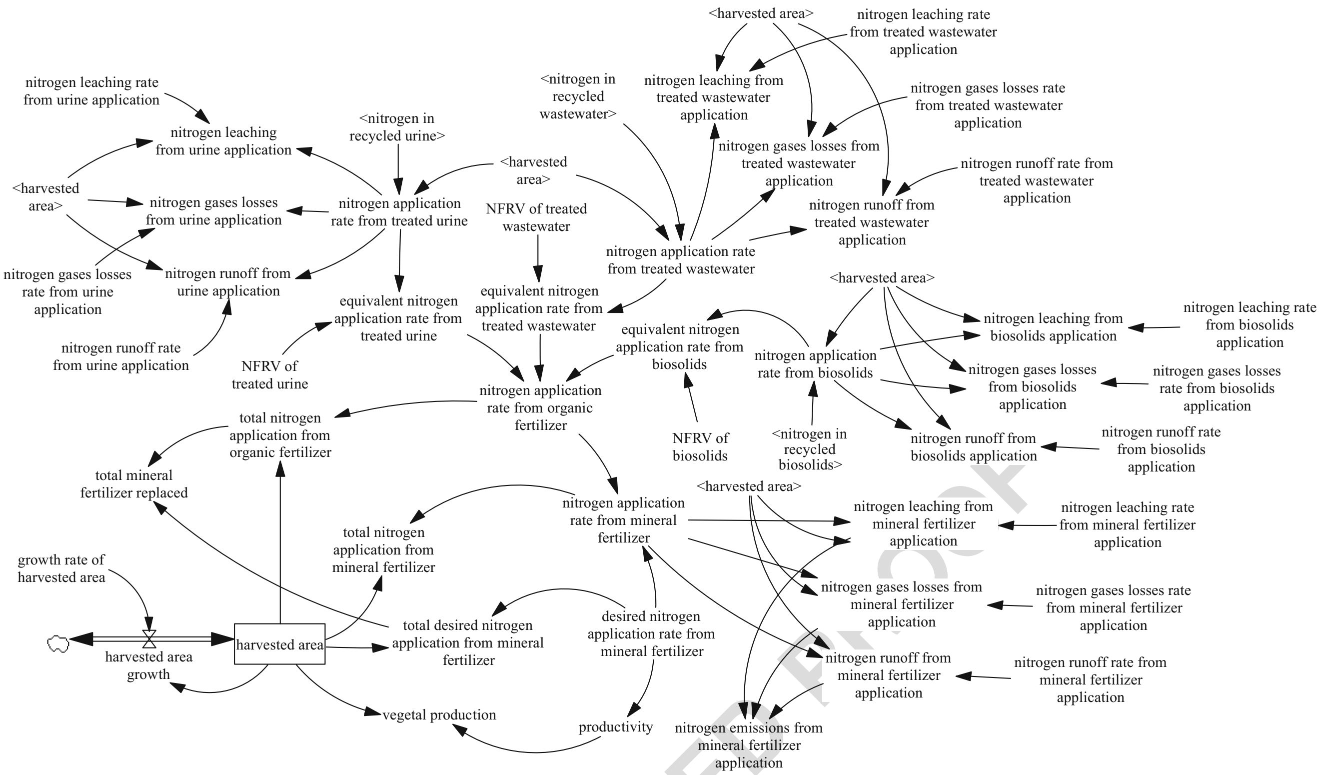


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Fig. 5 Vegetal production subsystem

ecosystems were calculated by sum of *emitted reactive nitrogen to air*, *emitted reactive nitrogen to water*, and *emitted reactive nitrogen to soil* (Fig. 6).

Application of the model in an hypothetical region

In order to analyze the system behavior, the variables *population*, *total nitrogen excreted per year*, *nitrogen in wastewater production*, *total mineral fertilizer replaced*, and *emitted reactive nitrogen to ecosystems* were used as management indicator of the model.

Population dynamics

The population of the hypothetical region in 1991 (t0), 2000 (t1), and 2010 (t2) were defined in 400,000 (P0), 480,000 (P1), and 560,000 people (P2), respectively. From initial conditions, the population of the hypothetical region in 2050 was established in 805,169 people. The population increased around 1.7 times since year 2000.

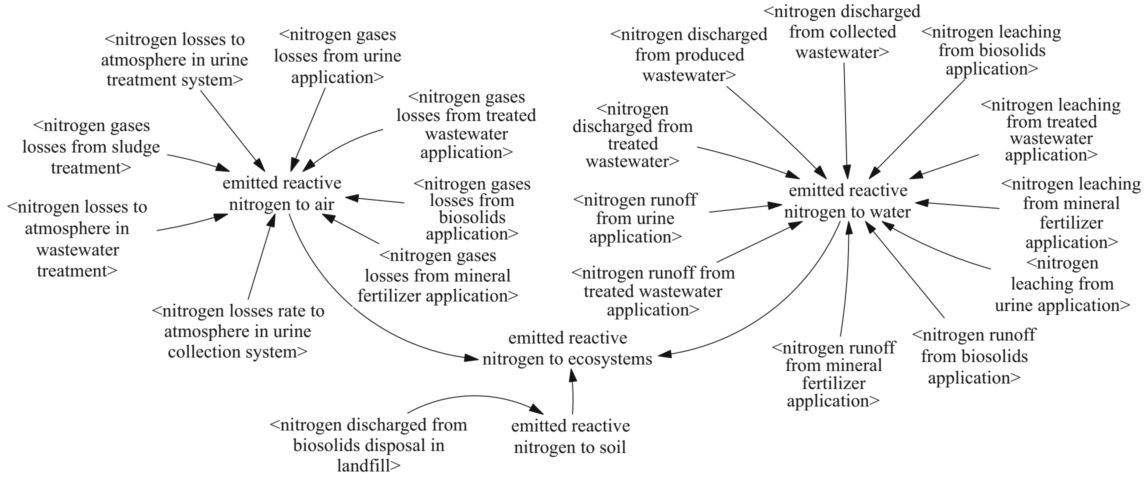

Fig. 6 Emitted reactive nitrogen to ecosystems

Human metabolism

Assuming average protein consumption of 75 g person^{-1} day^{-1}, being 67 and 33% of vegetal protein and animal protein (Smil 2011), respectively, the *nitrogen excreted* per capita *per year*, in 2000, was set around 4.4 kg N person^{-1} year^{-1}.

The protein digestibility rate was set as 90% for animal protein and 75% for vegetal protein (WHO 2007). Thus, in 2000, the *nitrogen in yellow water* and *nitrogen in brown water* were fixed in around 3.5 and 0.9 kg N person^{-1} year^{-1}, respectively. The conversion factor of protein to nitrogen (*conversion factor from protein to nitrogen*) was set at 16%.

The consumption of animal and vegetal protein in the simulation period is presented in Table 1. The protein consumption variation was set based on the world average evolution in protein consumption per capita, for the period between 1961 and 2011 (FAO 2016). The values were determined to archive an increase of 25 g in per capita protein consumption in 50 years, from 75 to 100 g person^{-1} day^{-1}. Thus, the *total nitrogen excreted per year* varied from 2067 t of nitrogen, in 2000, to 4702 t, in 2050.

Wastewater system

The nitrogen amount in gray water (*nitrogen in gray water*) was fixed at 0.74 kg N person^{-1} year^{-1}, being around 50% from kitchen water and 50% from bathing and washing water such as used by Magid et al. (2006). Thus, the *nitrogen in wastewater production* varied from 2416 t, in 2000, to 5298 t, in 2050.

It was assumed that the wastewater collection rate and wastewater treatment rate gradually grow in time, as shown in Table 2, initially as 60 and 30%, respectively. Based on Gronman et al. (2016), it was assumed that 30% of nitrogen inflow in wastewater treatment system leaves as sludge (*sludge production rate*) and 26% leaves as gases emissions by N_2 and N_2O (*nitrogen losses rate to atmosphere in wastewater treatment*).

The nitrogen amount that will enter in the wastewater collection and treatment systems, by 2050, will be 4716 and 3690 t, respectively. The available *nitrogen in produced sludge* increased from 5.4 to 20% of nitrogen in produced wastewater. Figure 7 shows the evolution of variables *nitrogen in wastewater collection*, *nitrogen in wastewater production*, *nitrogen in wastewater treatment*, and *nitrogen in produced sludge*.

Table 1 Protein consumption (g person^{-1} day^{-1})

Year	Animal protein	Vegetal protein	Total protein
2000	25	50	75
2010	25.5	53	78.5
2020	26	58	84
2030	29	60	89
2040	32	62	94
2050	35	65	100

Table 2 Wastewater collection and treatment rates

Year	Collection rate	Treatment rate
2000	0.6	0.3
2020	0.7	0.5
2040	0.8	0.7
2050	0.9	0.8

Mineral fertilizer demand

The *desired nitrogen application rate from mineral fertilizer* was set in 170 kg N ha^{-1} year^{-1}. The *harvested area* in 2000 was considered to be 50,000 ha. The *growth rate of harvested area* was assumed to be 0.1% per year. Thus, *total nitrogen application from mineral fertilizer* varied from 8500 t, in 2000, to 8935 t, in 2050.

Total nitrogen emissions to ecosystems

The *emitted reactive nitrogen to ecosystems* was calculated by sum of all emissions from wastewater system, urine segregation system, and vegetal production system by treated wastewater, biosolids, treated urine, and mineral fertilizer. The nitrogen losses were determined through leaching, runoff and gases emissions rates.

Nitrogen losses from the application of fertilizers were assumed to be similar to those reported by Zhang et al. (2013) for China. Those are 1% for N_2O emissions, 12.9% for NH_3 losses, and 9.8% for NO_3^- losses. These numbers can be compared to others found in the literature. Bouwman et al. (2002) estimated that world average of NH_3 losses in application were 14% (10–19%) for mineral fertilizer and 23% (19–29%) for animal manure. IPCC's methodology uses an emission factor of 0.01 (1%) for N_2O emissions (De Klein et al. 2006). Gu et al. (2015) assumed loss rates from organic

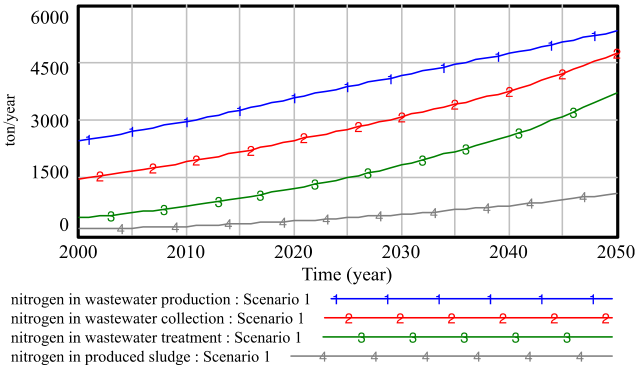

Fig. 7 Evolution of nitrogen flows in the wastewater system

fertilizer application in 23, 15, 4, 5, 1, 0.7% for NH_3 emission, denitrification, leaching, runoff, N_2O emission, and NO emission.

In this study, the loss rates through leaching, runoff, and gases emissions in application of mineral fertilizer and treated urine were set to 5, 5, and 15%, respectively. For treated wastewater and biosolids, the losses rates were assumed to be those used by Gu et al. (2015), being 4, 5, and 25% for leaching, runoff, and gases emissions, respectively. Application of these values lead to an *emitted reactive nitrogen to ecosystems* varying from 4.5 to 7 t of nitrogen between year 2000 and 2050.

Scenarios for new policies of nitrogen management

Six scenarios where considered in this study.

> Scenario 1—no nitrogen is removed from wastewater in the region

The first results shown in section 4 were determined for Scenario 1. In this scenario all nitrogen excreted that enters in wastewater system is emitted to the environment. That is, there is no recycle and no replacement of mineral fertilizer in the system.

> Scenario 2—no nitrogen is removed from wastewater in the region, which applies advanced agricultural practices

Scenario 2 is an improvement of Scenario 1. Here, the efficiency of mineral fertilizer application was assessed. It was assumed a reduction of 20% in mineral fertilizer demand from improving of nitrogen use efficiency without reduction of yield. Thus, the *desired nitrogen application rate from mineral fertilizer* was set in 136 kg N ha^{-1} $year^{-1}$.

> Scenario 3—nitrogen is recovered from wastewater in the region

This scenario considers nitrogen recycling from treated wastewater and biosolids in a traditional approach. The recycling rate of treated wastewater and biosolids were defined in Table 3.

To determine the mineral fertilizer replaced by the application of treated wastewater, the nitrogen fertilizer replacement values published by Gutser et al. (2005) where applied. These authors indicate that the mineral fertilizer equivalent of sewage sludge vary between 15 and 30%. The Nitrogen Fertilizer Replacement Values of treated wastewater and biosolids were assumed to be 60 and 25%, respectively.

Table 3 Recycling rates of treated wastewater and biosolids in the hypothetical region

Year	Wastewater	Biosolids
2000	0.0	0.0
2010	0.1	0.1
2020	0.25	0.3
2040	0.35	0.6
2050	0.5	0.8

> Scenario 4—urine is segregated at the source and no N is removed from wastewater

In order to analyze the effects of urine segregation, in this scenario it was assumed that all N recovered comes from treated urine. The NH_3-N losses in segregation and collection system where set to be 0.1% following Jönsson et al. (2000) work quoted by Spangberg et al. (2014).

NH_3-N losses in urine treatment by storage were considered to be 4% as measured by Karlsson and Rodhe (2002) in storage of animal urine, and used by Spangberg et al. (2014). The NFRV values of urine vary between 90 and 100% (Gutser et al. 2005). This study considered this value to be 100%. The *urine segregation rate* is indicated in Table 4.

> Scenario 5—nitrogen is recovered from three sources: treated wastewater, biosolids, and segregated urine

This scenario represents the sum of Scenario 3 and 4 to show a transition between scenario of treated wastewater and biosolids recycling and scenario of treated urine recycling.

> Scenario 6—nitrogen is recovered from treated wastewater, biosolids, and segregated urine, and a policy for the stabilization of protein consumption is in place

Scenario 6 considers Scenario 5 and ads the effects of a successful policy for the stabilization of protein consumption from 2030 onwards maintaining a total protein consumption in 89 g $person^{-1}$ day^{-1}, being 29 g $person^{-1}$ day^{-1} of animal protein, and 60 g $person^{-1}$ day^{-1} of vegetal protein.

Table 4 Urine segregation rate

Year	Urine segregation
2000	0.0
2010	0.1
2020	0.3
2040	0.6
2050	0.8

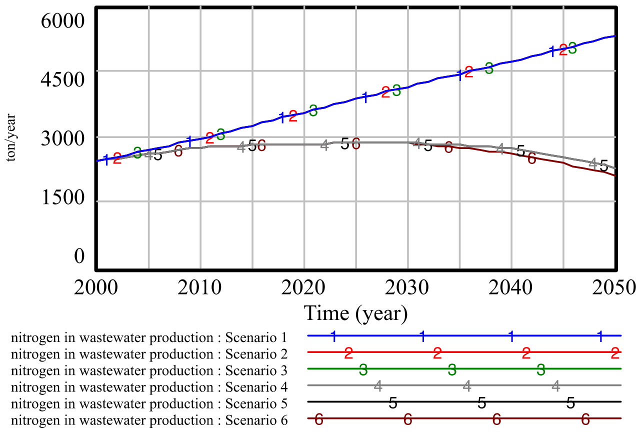

Fig. 8 Effects of urine segregation in the wastewater system on the overall deposition of N in the region considered

Results

Quantitative effects of urine segregation

Figure 8 shows the quantitative effects of urine segregation from wastewater. For the considered values of *urine segregation rate*, in 2050, around 40% of *nitrogen in produced wastewater* would be segregated, as indicated for Scenarios 4, 5, and 6.

Total mineral fertilizer is replaced by nitrogen from waste sources

Figure 9 shows the *total mineral fertilizer replaced* from the considered scenarios. Scenario 5 shows the higher potential of mineral fertilizer replacement in 2050, which represented about 46% of nitrogen fertilizer use. Stabilization of protein consumption from 2030, as considered in Scenario 6, can lead to a nitrogen fertilizer replacement of 41.3%.

Scenario 4, only urine recycling, shows to be more efficient than Scenario 3, which occur only treated wastewater and biosolids recycling. This occurred due to the nitrogen losses rates of treated wastewater and biosolids recycling system are higher than in urine recycling system.

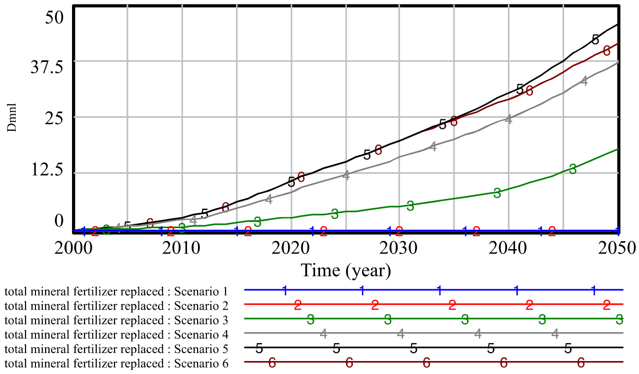

Fig. 9 Total mineral fertilizer replaced

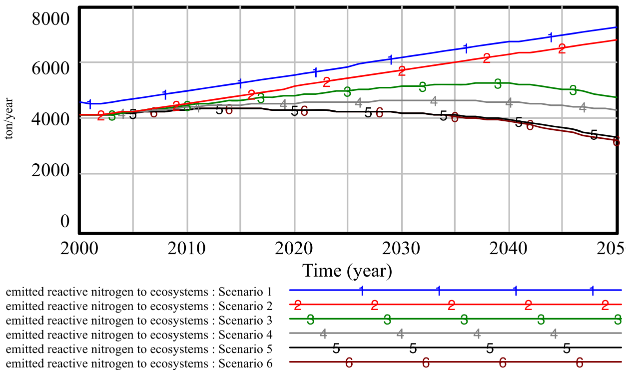

Fig. 10 Emitted reactive nitrogen to ecosystems from six scenarios

Nitrogen emissions to environment

Figure 10 shows the *emitted reactive nitrogen to ecosystems* from all scenarios. As expected, in Scenario 1, where nitrogen recycling does not occur and has the highest rate of mineral fertilizer application, *emitted reactive nitrogen to ecosystems*, represents more than twice the one shown in Scenario 6, where recycling of treated wastewater, treated urine and biosolids, and stabilization of protein consumption, are considered.

Conclusions

A model of decision support systems for the management of reactive nitrogen found in wastewater systems has been presented. It is shown that considering action in multiple sectors, including cultural and technological changes, a reduction of more than half of the disposal of reactive nitrogen in the environment can be achieved. The model allows to identify the effects of different variables in the task to reduce anthropogenic deposition of reactive nitrogen in the environment.

Whereas nitrogen flows are well-known, the analysis of its components and their relationships allows a better and more complete understanding of this phenomenon. The proposed model permits to identify the main variables of subsystems population, wastewater, urine segregation, and vegetal production, and its interactions. The model can indicate the nitrogen availability and use, and their efficiencies.

For the actions proposed in six scenarios, the urine segregation and stabilization of protein consumption showed to be more effective in relation to reduction of nitrogen emissions to environment and potential of nitrogen recycling. The proposed model permits the formulation of new policies for nitrogen recycling in a region. It also helps decision-making for a more effective management of reactive nitrogen flows.

New scenarios to promote the urine segregation system should be tested from aspects as technology change in water and sanitation sector from economic incentive, reduction of negative impact on health and environment from government policy, and changes of educational aspects to use and accept the new sanitation system.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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