HOW TO RE-BALANCE THE NITROGEN METABOLISM OF THE ATLANTA-CHATTAHOOCHEE SYSTEM?

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Abstract. A Multi-sectoral Systems Analysis (MSA) of the Atlanta-Chattahooche system is proposed. It has three objectives: (i) to identify the major fluxes of nitrogen (N) entering, leaving, and circulating within an urban-rural system; (ii) to quantify the benefits of implementing changes of technology in that system; and (iii) to assess the relevance, or redundancy of the system's features – sectors, processes, and flows – for attaining proposed goals for improving the eco-efficiency and eco-effectiveness of the system. MSA uses Substance Flow Analysis (SFA) to track the paths of N through a structured model comprising five socio-economic sectors, i.e., water, energy, food, forestry, and waste management. It incorporates a set of eco-effectiveness indicators, to assess the health of the nitrogen metabolism of the system, as well as a Regionalized Sensitivity Analysis (RSA) procedure for identifying economic and policy priorities for re-balancing the flows of N. The capabilities of such a framework are illustrated in the context of the Atlanta-Chattahoochee system under different scenarios for three candidate technological solutions: (a) urine separating toilets, (b) pyrolysis of poultry litter, and (c) capturing power plant flue gas for algae production. The results show that MSA can be useful for understanding the nitrogen metabolism of the city-watershed system while also indicating which innovative technologies might be most effective in "re-balancing" that metabolism.

INTRODUCTION

The flows of materials and energy entering a region or system, their transformation within it, and then exit from it – often referred to as the metabolism of that system – are an indication of how resources are used and how this affects the environment, typically in the form of wastes and emissions. A large body of studies has suggested the need for closing the cycles of materials and nutrients. The use of non-renewable nutrients (e.g., phosphorus) and materials (e.g., fuels), only then to render them as wastes and emissions, does not seem a sustainable practice. Employing large amounts of energy to return reactive species of nitrogen (N) as inert nitrogen gas to the atmosphere (e.g., through biological nitrification and denitrification of wastewater) does not make much sense, if more energy and non-renewable materials are then required to recapture the inert N in the atmosphere for fertilizer production (e.g., through the Haber-Bosch process, based on methane).

The following sections describe a computational framework for assessing the health of the N metabolism of a human-manipulated system. With this capability, it is expected that MSA will be able to generate insights into what might be implemented, through simulation, before putting solutions into practice. The specific objectives of the present work are oriented towards: (i) identifying what are the most significant flows of N associated with the system; (ii) assessing the effects, across various socio-economic sectors, of implementing a given technological innovation; and (iii) ranking the relevance of elements of the system for improving, or diminishing, the chances of achieving proposed targets, such as re-balancing the N metabolism.

METHODOLOGY

(1) Multi-sectoral Analysis

In order to achieve the three objectives proposed for the Multi-sectoral Systems Analysis (MSA), its framework is built upon three components. First, there is the methodology of Substance Flow Analysis (SFA), for tracking and quantifying the flows of specific substances through a system (Brunner and Rechberger, 2003). In this case, SFA is based on detailed flow diagrams elaborated for five socio-economic sectors: water, forestry, food, energy, and waste management. Each sector is represented by flows and unit processes that include the principal human and environmental factors affecting the system. Unit processes are those activities that involve the mixing, separation, or transformation of flows. Further background details for the present application can be found in (Villarroel Walker, 2010). Figure 1 summarizes the five sectors involved. Sectors are interconnected with each other and with the environment, i.e., the hydrosphere, lithosphere, and atmosphere, through material and energy flows. Flows are those of water (H2O), elemental Nitrogen (N), elemental Carbon (C), elemental Phosphorus (P), and energy (E). Some flows are calculated as a function of consumption patterns, their composition, and a calorific value. For instance, the nutrient input in the form of food can be estimated by knowing a typical food intake per person and multiplying this by the population. However, most flows are computed based on the material and energy balances associated with the equations describing the unit processes, e.g. biological wastewater treatment.

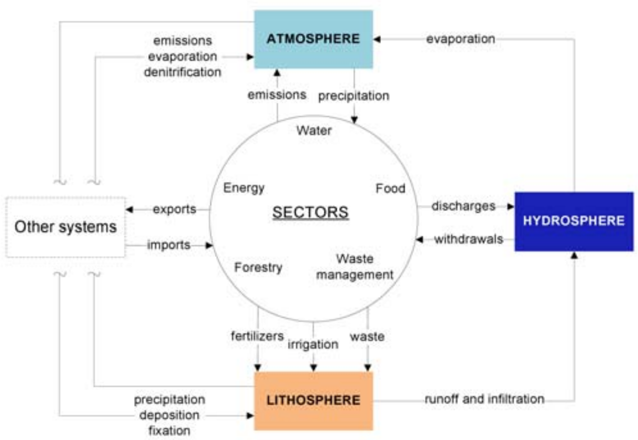

Figure 1. Simplified scheme of the MSA structure.

(2) Environmental Indicators

This second component involves the definition of environmental indicators for the practitioner to assess the improvement (or worsening) of the system's performance, as a result of the introduction of structural and/or operational changes. Furthermore, in addition to the insights that can be drawn from analyzing how flows change (due to the introduced change), indicators can reveal whether the system, as a whole, has benefitted from this change or, in other words, has achieved a more balanced state. A structural change refers here to the introduction of a new unit process or the rerouting of a flow, while an operational change is regarded as the adjustment of the behavior of an existing parameter, such as an advance in car-combustion efficiency. In the present paper, three indicators are utilized: (1) HAE assesses the health of air emissions; (2) HWE represents the health of emissions to water bodies; while (3) WEF is a measure of the productivity of the system from an eco-effectiveness perspective. These indicators are based on the concept of eco-effectiveness (Braungart et al., 2007), which has been applied in product and systems design for achieving a truly sustainable system, where material cycles are closed and nothing is wasted, i.e. "waste = food". The numerical calculation of the indicators requires the definition of a *reference* state, deemed to be a well balanced (sustainable, perhaps) state of the system. This state is strongly related to the objectives and expectations of the specific case to which the MSA is being applied. The mathematical form of these indicators is explained in previous work (Villarroel Walker, 2010).

(3) Regionalized Sensitivity Analysis

The third component of the MSA is that of Regionalized Sensitivity Analysis (RSA). RSA allows MSA to account for the inherent uncertainty of the data and the model structure. More importantly, however, RSA can reveal which elements of the system are critical, or redundant, for attaining proposed targets, which can be defined based on a level of improvement in the three indicators (i.e., HAE, HWE, and WEF) towards a more balanced, sustainable state. Extensive work has been done in environmental modeling under uncertainty using RSA and more detailed explanation of the procedure can be found elsewhere (Osidele and Beck, 2003; Spear and Hornberger, 1980).

CASE STUDY

Regional Context

Our case study is the Upper Chattahoochee Watershed (UCW), located in north-central Georgia (Figure 2). With a total surface of 4,093 km^2 and 1.3 million inhabitants (in 2000), the UCW covers nearly a quarter of the Metropolitan Atlanta area. The UCW has a variety of land uses including significant poultry production and silviculture. In 2000, land cover was mostly forest (53%), followed by urban and sub-urban (29%) and pasture and crops (10%). About 10% of the electricity demand is satisfied by the McDonough Power Plant with a total capacity of 580 MW. 85% of its capacity relies on coal combustion, with the remainder being natural gas.

Data Collection

The magnitude of material flows can change significantly from one region to another due to differences in consumption patterns, process efficiencies, land use, and other factors. Most of the data are retrieved from official sources, such as the Environmental Protection Agency (EPA), Georgia Department of Natural Resources (GA DNR), US Department of Agriculture (USDA), US Geological Service (USGS), the US Census Bureau, the Food and Agriculture Organization of the United Nations (FAO), and the Intergovernmental Panel on Climate Change (IPCC). Due to data availability, simulations are carried out for data corresponding to the year 2000. The last estimated water use data reported by USGS corresponds to that year, while the last two USDA agricultural censuses are for 1997 and

2002. Energy data are typically available on an annual and, in some cases, monthly basis. Although this study tries to use local data as much as possible, these are not always available. For these cases, regional or national data are acceptable. The uncertainty associated with the use of non-local/specific data is incorporated in the model and addressed by the RSA procedure.

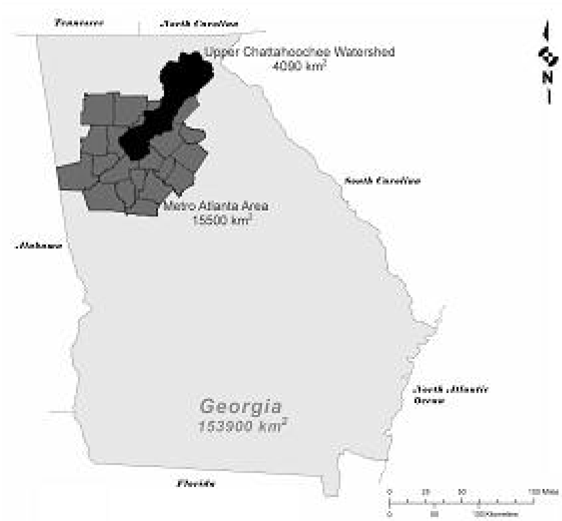

Figure 2. The Upper Chattahoochee Watershed with respect to Georgia and the Metro Atlanta Area.

Nitrogen Flows

The present work focuses only on flows of N. This is the most abundant element in the atmosphere and one of the most studied substances, given its involvement in almost every aspect of nature and human activities. Food production relies heavily on synthetic fertilizers as a source of N, whose synthesis requires the use of methane, largely from fossil origins, and atmospheric N. Fossil fuels also contain N, which after combustion is released in the form of nitrogen oxides (NO_x) and other compound N forms. Land application of manure and fertilizer is responsible for the emission of ammonia (NH_3), a gas known for its adverse effects on human and animal health. Nitrous oxide (N_2O), an ozone-depleting substance, is also emitted and is a powerful greenhouse gas, with, therefore, importance for climate change. It has natural sources (mainly microbial action in forests) and human-associated sources, such as agricultural soils, manure handling, and fossil-fuel combustion.

Scenario definition

One of the objectives is to utilize MSA for investigating the effects that three technological innovations, considered as structural changes, might have in one or more sectors, and on the system as a whole. These innovations are defined as: (i) Urine Separation Technology (UST) (Larsen and Lienert, 2007), (ii) Poultry Litter Pyrolysis (PLP) (Das et al., 2008), and (iii) Algae Production from power plant Flue gas (APF) (Kadam, 2001). Although these technologies are usually associated with different socio-economic sectors – the water, food, and energy sectors respectively – their ultimate goals are the recovery of nutrients for fertilizer and energy production. Such productions are to be achieved by manipulating N flows and generating a product capturing material that would otherwise be released as an unnecessary emission or a waste, with the exception of PLP. UST collects nutrients present in urine before they are mixed with pollutants and diluted in the sewer system. N is otherwise destined to be released to the atmosphere during advanced biological treatment in wastewater treatment facilities. APF is typically considered for recapturing part of the carbon released in coal combustion. However, growing micro-algae also requires N as a nutrient, which in principle can be obtained from the same flue gas stream by direct injection into the algae ponds. This must be supplemented with processes for producing fertilizer from elemental N and NO_x, such as the Haber-Bosch and the Electro-Bean processes, respectively. PLP, on the other hand, diversifies the use of poultry litter by producing inorganic fertilizer and biofuels, in contrast to its most typical use solely as fertilizer.

These manipulations are envisioned as possible opportunities for re-balancing the N metabolism of the Atlanta-Chattahoochee system. With these three technologies, five scenarios are defined: the base case, or 0% technology implementation, 100% implementation of UST, 100% implementation PLP, 50% implementation of APF, and finally all three technologies implemented at the same time and at the same levels as individually.

An arbitrary improvement of 30% for all three indicators (HAE, HWE, and WEF) is imposed as the target for the RSA procedure. This enables the MSA to identify which elements in the system might be critical to the task of moving closer to re-balancing the N metabolism in the UCW. However, it is still necessary to define a *reference* state against which the performance of the system is to be compared. For the purposes of this study, the reference state is assumed to be an undisturbed southeastern forest occupying the same area as the UCW.

RESULTS AND DISCUSSION

Major Flows of Nitrogen

Table 1 presents the ten largest flows in the system for the base-case simulation. For a region with a prominent poultry industry, it is not surprising that the major flow is feed/fodder for livestock. This is mostly imported from outside the watershed. About 85% of it is used by the poultry industry, while the remaining 15% is for cattle and swine. Slightly less than 60% of the feed is converted into fresh manure. Local use of fuels for domestic, commercial, industrial, and transportation purposes is responsible for over 26,000 t $N{\cdot}a^{-1}$, of which nearly 88% is associated with the combustion of natural gas, mostly for industrial and domestic use. Similar in magnitude, imports of coal and natural gas are two important flows. The first is mostly used for power generation (about 90%), satisfying 10% of the electricity demand within the watershed. Although the N content in coal is typically low, some 1.5% in weight depending on the type of coal used, emissions from coal combustion accounts for about 90% of the 20,000 t $N{\cdot}a^{-1}$ released from power-generation operations.

Table 1. Major flows of nitrogen (base case)

Description	N flow [b] (t N/a)	standard deviation
Feed consumption by livestock	27808	1874
Emissions from fuel consumption[a]	(26898)	7849
Imports of coal	+26405	2687
Imports of natural gas	+25865	8536
Emissions from power generation	(20235)	2000
Applied to soil as fertilizer	13069	733
Influent of WWTPs	10054	2659
Food consumed	9489	327
Landfilled material (PWYFC)[c]	6695	624
Coal Combustion Products (CCP)	6357	647

[a] Non power applications: domestic, commercial, industrial and transportation.

[b] Values in parenthesis are flows exiting the system, values preceded by the '+' symbol are entering the system, and the rest are internal flows within the system.

[c] PWYF refers to paper, wood, yard waste, food, and Coal Combustion Products.

More than 70% of the N applied to soils (13,000 t $N{\cdot}a^{-1}$) is imported as inorganic fertilizer. The remaining requirements for N fertilizer are satisfied by municipal sludge or poultry litter. Before its application, about 35% of the N in poultry litter is lost due to volatilization during handling and storage. The sewage collected by the sewer system, and later treated by wastewater treatment plants, accounts for 10,000 t $N{\cdot}a^{-1}$, about 36% of which is urine. The advanced biological treatment process, exemplified by the R. M. Clayton Water Reclamation Facility in Atlanta, reduces the N content in sewage by about 85%. Most of this reduction (70% of the influent) results in the release of N to the atmosphere, while the rest remains in the sludge.

Total consumption of food represents another 10,000 t $N{\cdot}a^{-1}$. Nearly 65% of that is converted to human waste (urine and feces) to be distributed into the sewer system and septic units. Although omitted in Table 1, food production – represented largely by poultry meat – is of the same order of magnitude as food consumption. "Domestic" consumption within the UCW of meat products produced therein is nearly 4400 t $N{\cdot}a^{-1}$. Therefore, most of this domestic production is exported. Food represents just over 15% of the N sent to landfills. Coal Combustion Products (CCP) are the most significant component of flows to landfill, although some 34% of CCP does find an alternative use.

With regard to the variability of the results, the largest uncertainty – an estimated standard deviation of about 30% of the average value – is associated with the N content in natural gas, as revealed by the flows of imports of natural gas and emissions from fuel consumption (non-power). The highest N content of natural gas is over three times that of the lowest, according to the relevant data. Likewise, the N content in wastewater is highly variable (standard deviation of 26%). All other flows have an uncertainty at or below 10%. Under such uncertainty, we may conclude that N flows in animal feedstuffs and fossil-fuel consumption are roughly equivalent. On occasion, however, the flow of natural gas will dominate.

Technology Assessment

Since the three technologies applied are associated with the N flows listed in Table 1, their implementation could have a noticeable impact on the system's metabolism. Compared with the other two technologies, UST takes care of a relatively small amount of N at the watershed level, i.e., 4,000 t $N{\cdot}a^{-1}$, but contributes to reducing N air emissions and discharges (effluent) from wastewater treatment by some 36% (2,600 t $N{\cdot}a^{-1}$) and 30% (550 t $N{\cdot}a^{-1}$) respectively. A similar amount of N is separated into the sewage sludge, which is mostly sent to landfill. PLP recovers N in the form of bio-oil (3,000 t $N{\cdot}a^{-1}$), biogas (500 t $N{\cdot}a^{-1}$), and fertilizer (900 t $N{\cdot}a^{-1}$). The dependence on imported inorganic fertilizer can be reduced by more than 10%. Implementing APF at a 50% level has the potential for capturing about 10,000 t $N{\cdot}a^{-1}$ of which some 18% is associated with NO_x (an indirect greenhouse gas) under uncontrolled conditions. Direct bio-oil extraction from micro-algae represents nearly 2,800 t $N{\cdot}a^{-1}$, while the remaining biomass, if subject to pyrolysis, has the potential for yielding an additional 4,200 t $N{\cdot}a^{-1}$ bio-oil, 670 t $N{\cdot}a^{-1}$ biogas, and 1,200 t $N{\cdot}a^{-1}$ fertilizer.

Table 2 shows that the implementation of APF achieves the best performance, at least in terms of reducing N loss through air emissions and improving system productivity. UST has marginal effects, possibly because of the limited amount of N handled in comparison to the energy sector.

Yet it is the only technology that offers some improvement in terms of undesirable emissions to water bodies. PLP on the other hand, seems to have no effect on emissions and, in addition, a negative influence on WEF (eco-effectiveness). This indicator is in part associated with the amount of N that exits the system in the form of a product, and PLP reduces the amount of poultry litter (treated as a source of N fertilizer) that is exported from the UCW. Because the ratio between products (outputs that are not deemed as waste or emission) and the resources consumed by the system is about 15%, the effect of reducing the generation of products is relatively more influential than the reduction in the demand for resources, hence the poor performance of WEF. As shown in Table 3, there are indeed economic benefits from converting poultry litter into fuels and fertilizer, but PLP does not reduce the magnitudes of undesired air and water emissions of N (at least not significantly at the watershed level). Joint implementation of all three technologies has mixed results: air emissions are notably reduced but productivity scores are poor.

Table 2. Indicator values for all five scenarios expressed as percent change

	HAE	HWE	WEF
Base case	0	0	0
UST	5	2	2
PLP	0	0	-31
APF	18	0	15
All three together	25	2	-19

Table 3. Benefits of technology implementation

	Fertilizer		Energy	
	t N/a	million $	GWh/a	million $
UST	4,000	4.3	0	0
PLP	900	1.0	270	12.5
APF	1200	1.3	510	28.0
All	6100	6.7	790	41.4

Table 3 shows the potential amount of fertilizer (in N terms) and energy (in the form of biodiesel and biogas) that each technology alternative could generate, together with its equivalent market value. Although this paper is focused on the metabolism of N, the economics of its manipulation reveal, in a subtle way, the potential incentive that could trigger a city-watershed initiative for re-balancing N flows. Coupling technologies that generate fertilizer with those that can produce fuels has increasing potential. APF is the technology that seems to have a distinct advantage with respect to economic potential and re-balancing the N metabolism. However, technologically, it is also the most complex candidate. A more complete cost analysis – including capital, operation, and maintenance costs – might reveal that the actual economic benefit is not too dissimilar from that of the other two candidate technologies. The economic component of Table 3 is therefore supplied as a reference to indicate potential market value of the products generated by UST, PLP, and AFP. Although these three technology alternatives can be associated with specific socio-economic sectors (water, food, and energy), there is clearly a business opportunity that can benefit from the *synergy* among the multiple sectors, as revealed by the MSA.

Key Elements for Improving the Nitrogen Balance

The RSA results are summarized in Table 4. It is noticeable that the improvement of indicator HAE is related to processes that are not particularly manageable from the point of view of regulations and best practices. This signals that the system – as approximated by the model structure and possible parameter ranges – is not capable of reaching the imposed improvement target of 30%. In addition, the fact that the *reference* state is assumed to be similar to an entirely forested area renders natural processes as highly influential. However, there is subjectivity in defining any (desired) target for the sustainability of a system, not to mention a plurality of culturally conditioned outlooks on what constitutes "desirability" and "sustainability" (Beck et al. 2011).

Table 4. Key factors to achieve a 30% improvement.

	HAE	HWE	WEF
Pervious area infiltration		X	
Monthly cloudiness		X	
Nitrogen fixation rate[a]	X		
Denitrification rate[a]	X		
Nitrogen leaching factor		X	
% implementation of PLP			X
Surface runoff[b]		X	
N in natural gas			X
N in O horizon layer[a]		X	
N in dry deposition	X		
Air temperature		X	
Latitude of the region		X	

[a] Specific for forest land.
[b] Impervious areas.

In the case of HWE, the key factors in the model can be classified into three groups: (i) climate, represented by cloudiness, temperature, and latitude; (ii) water management, described by infiltration and runoff; and (iii) nutrient availability in soils, exemplified by leaching through soils and the nutrient content in the upper layer of soil. Although there is not much scope for manipulating the first group (in the form of policy or corporate action), it is an indication that climate change has a role in determining the health of the N metabolism of the UCW. The remaining two groups ((ii) and (iii)) can be addressed by considering, for instance, Integrated Urban Water Management (IUWM) (Beck, 2005) and adequate soil nutrient management.

The successful improvement of indicator WEF seems to be linked to the amount of (i) poultry litter that is kept as a product and (ii) N that enters the system as a resource but released to the atmosphere during natural gas combustion. With regard to the former, it might be possible to reveal other benefits of PLP that are more successful and relevant in re-balancing the N metabolism, by incorporating a measure that can assess the difference in state (hence, economic value) among different forms of N (e.g., as in inorganic and organic fertilizers).

CONCLUSIONS

With the goal of re-balancing the N metabolism of a system, the paper describes a framework for tracking the paths and transformations of N within that system and assessing the degree of improvement achieved by implementing candidate technological innovations. In principle, the framework is sufficiently generic to be applied to any urban-rural system and customized to any scenario. However, the degree of detail described by the MSA structure suggests that the best resolution is at the city, watershed, region, or country level.

The largest flows of N in the UCW are represented by the feed for livestock (largely for the poultry industry) and fossil fuels. The imports that fall into these two categories mobilize a staggering amount: 90,000 t $N \cdot a^{-1}$. Wastewater and solid waste, on the other hand, reveal themselves in a less dominant position, but still relevant at 20,000 t $N \cdot a^{-1}$. With regard to the three candidate technologies evaluated, UST provides more consistent re-balancing attributes across the indicators, while APF shows radical improvement in terms of air emissions and eco-effectiveness (i.e., “waste = food”). PLP on the other hand, scores poorly on the eco-effectiveness front because it takes N from a flow that is already considered a useful flow (a product).

Given that MSA tracks more than merely N flows, i.e., C, P, water, energy, and money as well, the results obtained for WEF (eco-effectiveness) suggest that evaluating the system only for one aspect (N) would not reveal trade-offs among substances, which is critical for any decision making process.

It is acknowledged that the concepts and computational tools described in this paper are centered on the technical aspects of sustainability, and that the realization of any structural or operational change (e.g., technical innovation, policy action) is subject also to its economic feasibility and acceptability to society. In the particular case of urine separation (i.e., UST), the Novaquatis project makes a significant contribution to exploring the social legitimacy of this technology (Larsen & Lienert, 2007). On another front, from the perspective of Cultural Theory, Beck et al. (2011) explore an approach to identify those elements of governance that promote, or hinder, actions that could contribute positively to re-balancing a systems metabolism.

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