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Understanding the metabolism of urban-rural ecosystems

A multi-sectoral systems analysis

R. Villarroel Walker · M. B. Beck

Abstract A Multi-sectoral Systems Analysis (MSA) methodology is presented as a tool for identifying the level of importance of flows of energy and materials (water, nitrogen, phosphorus, and carbon) as they pass through an anthropogenically manipulated system. That system comprises a web of processes, across a total of five industrial sectors: water, forestry, food, energy and waste management. Given the heterogeneous nature and quality of data sources, the propagation of data uncertainty is considered through a Regionalized Sensitivity Analysis (RSA) procedure, based on the Monte Carlo simulation approach. The MSA reveals the advantages of studying different material cycles simultaneously, in addition to interpreting them individually, while gaining insight into the magnitude of the associated flows. The proposed framework is illustrated for a case study of the Upper Chattahoochee Watershed, in which parts of Metro Atlanta are located. Results show that natural flows are predominant in the water and energy cycles. Direct human manipulations of water, i.e., withdrawals for public supply and power generation, are less than 25% of the amount received as precipitation. Solar input is 200 times the total demand for electricity. Apart from sun-light, gasoline for transportation is the flow with the largest content of energy; it is responsible for providing 71% of the total demand of fuels for uses other than power generation. In contrast, cycles of nutrients such as N and C are strongly related to the flows of fuels, mainly coal and natural gas. In a second tier, fertilizer use and the poultry industry in the region are significant for the use of nitrogen. Phosphorus fluxes are similarly dominated by the food sector and, as a consequence, to a lesser extent by the water sector, because of water's role as a waste-conveyance medium.

Keywords Substance flow analysis · Phosphorus · Resources · Waste management · Energy · Nitrogen · Carbon · Urban metabolism

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Introduction

Cities and their metabolism

With more than half the world's population dwelling in cities, the role of urban areas—as drivers of consumption and pollution—has become prominent in the discussion of sustainable development (Rees and Wackernagel 1996). The behavior of cities has been compared to that of biological organisms, with an uptake of resources and the consequent release of wastes, whose impacts go well beyond the city's geopolitical boundaries (Hillman and Ramaswami 2010; Rees and Wackernagel 1996; Peters 2010). The flows of materials that satisfy the needs and wants within cities are commonly associated with the distortion or disruption of natural, and typically self-organizing, biogeochemical cycles (Beck et al. 1994; Beck and Cummings 1996; Browne et al. 1994). The benefits of circular metabolic movement of resources and nutrients for the sustainability of cities are well known (Deelstra and Girardet 2000).

The metabolism of a region, as interpreted herein, is the reflection of the performance of a conglomerate of systems—industrial systems and sectors—with sometimes complex interactions among them, in the form of flow rates of materials (e.g., in tonnes per year) and energy (e.g., in kWh per year). The relevance of a certain substance or material depends on the economic activities that take place in the region, city, or nation under study, and can vary among economic sectors as well. For instance, phosphorus is an important element in the manure generated by the livestock industry in Finland, but nitrogen is not as significant. For the same region, nitrogen, as opposed to phosphorus, is more significant for the energy sector. However, the largest flows of these two substances are associated with the consumption of fertilizers, as expected, given the relevance of the agriculture industry at the national scale (Antikainen 2007). Only through systematic analyses may the often hidden synergies between sectors and materials be revealed and investigated. Three types of understanding are critical for assessing those processes that threaten or contribute to sustainable development (Kennedy et al. 2007): (a) the role of biogeochemical cycles in the metabolism of cities; (b) the material and energy exchanges between urban areas and their hinterlands; and (c) how the environment influences these cycles.

Conceiving of the metabolism of an urban system has been present since Wolman (1965) published his study of a hypothetical city in the US. Material Flow Analysis (MFA), a well established quantitative methodology (see, for example, Brunner and Rechberger 2003), is used for exploring the mechanisms associated with metabolism and material transformations and flows through socioeconomic entities—mostly at the national or regional level. In fact, MFA embraces a suite of methods with different objectives, e.g. Total Material Requirement (TMR), Material Intensity Per Unit Service (MIPS), and Substance Flow Analysis (SFA). This last, the specific methodology of the present work, can be employed for tracking substances, e.g. N, P, and C, by accounting for inflows, outflows, wastes, and emissions. SFA has frequently been used to trace persistent toxins, high-value recyclable materials, hazardous chemicals, or substances of regional concern. SFA applications range from budgeting (Antikainen et al. 2004) to decision-making in waste management for substances such as phosphorus and nitrogen (Tangsubkul et al. 2005; Bjorklund et al. 1999). When MFA is coupled with energy balances, it becomes a useful tool for the evaluation of socioeconomic metabolism and is capable of differentiating between energetically-dependent and material-dependent economies (Huang et al. 2006). Bauer (2009) discusses four prominent environmental issues in the US that can be investigated by using Material Flow Analysis: energy supply and demand, the green economy, supply chains and material production, and the underlying drivers of non-point source pollution. In relation to this last, the knowledge of which flows and processes are responsible for N and P accumulation within the system can contribute to identifying effective efforts to reduce the risk of eutrophication in water bodies. Substance Flow Analysis has been used before as a risk assessment tool, particularly in relation to carcinogenic substances, such as brominated flame retardants (Morf et al. 2008). Under the metabolism approach, MFA has shown its usefulness not only in illuminating human-nature interactions, but also in supporting public policies and action (Barles 2009; Hashimoto and Moriguchi 2004; Baker et al. 2007). However, in line with other environmental assessment tools, there is room for more emphasis on social and economic considerations, in the form of indicators such as health, employment, income, education, housing, and leisure (Sahely et al. 2003).

Vital cycles: Nutrients, water, and energy

The metabolism of a city or region is typically expressed in terms of four fundamental cycles: those of nutrients, energy, water, and materials (Kennedy et al. 2007). These cycles are representative of the inhabitants' behavior, the city infrastructure characteristics, and the surrounding environment (climate). Several metabolism studies have been carried out for urban systems with a focus on the flow of nutrients, through the food sector in Paris, France (Barles 2007), Linköping, Sweden (Neset et al. 2008) and Toronto, Canada (Forkes 2007), the wastewater system in Sydney, Australia (Tangsubkul et al. 2005), and households in the Minneapolis-St. Paul metropolitan area (Baker et al. 2007). It has been found that urban systems are typically disconnected from the immediate environment in terms of food and fuels, but very much dependent on the surrounding hinterland for matters such as water supply and the disposal of wastes (Decker et al. 2000). A more comprehensive study was undertaken for nitrogen and phosphorus at the national level in Finland, which included the food, forestry, municipal waste, and energy sectors (Antikainen 2007). These studies consider the flow of nutrients as a measure of consumption and emission generation, emphasizing the need for closing nutrient cycles as a means of reducing the economic, environmental, and social stresses derived from misplacing nutrients in the ecosphere.

In addition, it is well known that one of the most relevant, current challenges for science and engineering is that of securing safe, reliable, and accessible sources of food (nutrients), water, and energy, even in the face of climate variability. The connection amongst these factors is clear and key to multiple economic sectors. Fertilizer prices (nitrogen and phosphorus) have experienced a more than 7-fold increase since 1960 (USDA 2008), with consequences for crop and food-production costs. About 2.6 billion people have no access to improved sanitation, mostly in parts of Africa, Asia, and South America. Nearly a third of them, 884 million people, do not use improved drinking water sources (WHO/UNICEF 2010). Energy usage, on the other hand, relies heavily on non-renewable fossil-fuels, which is not sustainable, and also is associated with the 70% increase in greenhouse gas (GHG) emissions from 1970 to 2004 (IPCC 2007). Fuel prices skyrocketed in 2008, e.g., gasoline reaching about 410 cents per gallon in the US, coinciding with a 10-fold jump in fertilizer prices with respect to those of the 1960s. With (global) agricultural activities using about 70% of water withdrawals, water availability and climate temperature have a direct influence over the capacity for crop production. A mere increase of 3°C in the global average temperature will dramatically reduce cereal production—particularly in low-latitude regions—with a potentially negative impact on the already large figures of the undernourished population: 1.02 billion people worldwide in 2009, more than 60% located in Asia and the Pacific region (IPCC 2007). The effects of global climate change on water quality are not yet well understood, although initial research has been done in the water sector, for example by Beck et al. (2010) at the city-watershed level.

Crop prices and productivity are partly a function of the accessibility of macronutrients for soil fertilization, namely nitrogen (N), phosphorus (P), and potassium (K). Nitrogen is an abundant element in the atmosphere and one of the most studied substances, given its involvement in almost every aspect of nature and human life. Food production relies heavily on inorganic fertilizers as a source of nitrogen; current levels of food and timber production would not be possible without fertilization. About 39–68% of the fertilizer N is incorporated into crops, while less than 10% is lost via leaching (Dowdell and Mian 1982). The rest is lost via runoff or volatilization. In relatively undisturbed ecosystems, atmospheric deposition and fixation are the prevalent N acquisition processes. N is typically made available to crops in the form of ammonia, which is synthesized by an energy-intensive process called the Haber-Bosch process. This process involves the separation of air N by cryogenic distillation and then the formation of ammonia by a catalytic reaction of N and hydrogen—usually from a fossil fuel source. Phosphorus and potassium, on the other hand, are considered non-renewable resources because of their mineral origins. The main two uses of these minerals are soil fertilization and animal feed. P is more abundant than K, with conventional reserves in the order of 12,000 and 8,400 million tonnes respectively. However, the extraction and utilization rates of the two are quite different, resulting in an estimated reserve life of only 88 years for phosphorus and 325 years for potassium (Roberts and Stewart 2002). As for N, phosphorus is an essential nutrient for plants, animals, and humans, with the difference that the earth's crust is the largest P pool. Various forms of phosphate rock are mined as part of fertilizer production, but once this P is lost via erosion and runoff to the ocean bed, it is no longer accessible to humans. Hence, P is often considered a non-renewable resource (Cordell et al. 2009). Besides fertilization, deposition has become increasingly relevant due to human processes, such as combustion of fossil fuels, waste incineration, and soil tillage (Ahn and James 2001; Anderson and Downing 2006).

Carbon (C) is also an essential nutrient for all life forms on earth. Today it is well known for its links with greenhouse gases (GHG); it has become a benchmark element for measuring sustainability, in the form of a carbon footprint, for instance (Wiedmann and Minx 2008). Within the global carbon cycle, natural processes represent the largest components of C. The major pools are the ocean, soils, atmosphere, and vegetation, sorted from largest to smallest (Schlesinger 1997). An estimated 9.0 Gt C y^{-1} are associated with fossil fuel combustion and net vegetation destruction due to land use changes. Annual carbon releases from fossil fuels represent only 0.8% of the total amount in the atmosphere, but when compared with the carbon accumulation rate in the atmosphere, they constitute about 53% (Schlesinger 1997). Cities account for about 70% of global energy-related carbon dioxide (CO_2) emissions (Canadell et al. 2009). Riverine flows of carbon should not be disregarded as they amount to nearly 1.9 Gt C y^{-1} (Öquist et al. 2009). The major human-related sources of carbon for streams and lakes are runoff from manure land applications, sewage discharges, and urban runoff.

The driving force of water flows, hence the water sector, is precipitation. In general terms, once rainfall reaches the ground it could either infiltrate, generate rapid surface runoff, or evaporate. A portion of the infiltration water produces lateral interflow while the rest recharges the water table. The foregoing description summarizes the hydrological behavior of a mostly rural area or forest, but human activities can change the hydrology of a region by introducing reservoirs, altering water supply, and constructing impervious surfaces (Kaye et al. 2006). Therefore, when dealing with urban areas, there are other mechanisms that need to be considered as shown by different models proposed for urban systems (Mitchell et al. 2001; Beck 2005). Withdrawals from surface and underground sources provide water for a diverse range of uses such as domestic, commercial, public, industrial, agricultural, and power generation, the last two being the largest, e.g., accounting for almost 80% of all fresh water withdrawals in the US. Once used, water is typically returned to its source after treatment. The difference between withdrawals and discharges is regarded as consumptive water use, which is normally associated with discharges to septic tanks, land application of wastewater effluent, outdoor watering of gardens and recreational areas, agricultural irrigation, inter-basin transfers, and evaporation from power generation or industrial use.

An important step in understanding biogeochemical cycles in rural-urban ecosystems is to perform a detailed mass and energy balance (Baker et al. 2001). Energy is typically considered in the form of conventional fuels, i.e., fossil fuels and firewood, with electricity as an energy carrier (Baker et al. 2007; Hosier 1993; Kaye et al. 2006). However, besides anthropogenic sources, it is important to account for how systems interact with natural flows of energy, e.g. solar radiation and loss of heat by evapotranspiration (Sahely et al. 2003), as these flows might in the future become an eco-effective source of energy (McDonough and Braungart 2002).

Material flows and cross-sectoral interdependencies

The interaction between the energy and the water sectors has long been known, since power generation and fuel production require significant use of water resources, while the supply of water depends largely on energy for pumping and treatment. 49% of all water withdrawals in the US (21.6×10^3 m^3 s^{-1}) is for use by thermoelectric power plants (Barber 2009). The extraction of raw material for power generation also consumes water. For instance, mining of coal can require water in a range from 20 to 270 L MWh^{-1} (WEF 2009). On the other hand, the largest operational cost of water supply and wastewaster treatment is related to its energy consumption (Kenway et al. 2011). Significant work has been done to take advantage of the energy value of sewage (Khan and Daugherty 1992; Logan et al. 2005), which is basically a function of the organic carbon content in wastewater (Shizas and Bagley 2004). In the case of municipal wastewater, organics come mostly from household waste as a result of the intake of food. However, that is not the only intersection point between the water and the food sectors. The food sector itself is the second largest user of water—after the energy sector—responsible for 31% of all water withdrawals in the US. The degree to which these sectors are interwoven is the reflection of technology selection and personal choice. For instance, water withdrawals for power generation depend largely on the cooling technology adopted. Wet cooling tower systems require 30–50 times less water withdrawals compared to once-through or cooling pond systems (Feeley et al. 2008). In a more local context, the use of either the water closet or dry sanitation systens has significant implications for the operational and technological aspects of dowstream processes for separating and recovering valuable nutrients from the carrier medium, i.e. water (Beck et al. 2009).

Understanding the main flows in an economy and the sectors that manipulate these flows—of nutrients, water, and energy, in this particular case—can help to address resource management and environmental issues from the policy-making perspective. The motivation for our work with a Multi-sectoral Systems Analysis (MSA) is, first and foremost, to track and account for the movement in concert of several entities—water, energy, nitrogen, phosphorus, and carbon—into, around, and out of a regional-city system. With regard to shaping future policy interventions, the goal is ultimately that of maximizing the scope for exploiting synergies and minimizing antagonisms amongst the several inter-related economic sectors of the system (water, energy, waste-handling, food, and forestry). In this broader context, the role of MSA is to enable the identification of system-wide locations where technologies might be changed: first, to enhance the recovery of renewable energy from waste; and, second, to reduce or eliminate complementary unconstructive services associated with the various material flows, typically, in polluting emissions to the water, air, and land environments. Having identified promising candidate technological substitutions, it would then be necessary to assess their promise from the perspective of their economic feasibility and potential environmental impacts (greenhouse gas emissions, ecological footprint, etc), both over their life cycles and along their entire supply-value chains, i.e., beyond the confines of the system's spatial/geopolitical definition (as necessary). These trans-boundary implications of the internal metabolism of cities have been addressed by accounting for, for instance, the embodied carbon (Hillman and Ramaswami 2010) and phosphorus (Matsubae et al. 2011) of goods. The influence on the city's hinterland, often expressed in the city's "footprint" (Rees and Wackernagel 1996; Peters 2010), could be seen as a reflection of the degree of non-circularity of the city's metabolism (Spiegelhalter and Arch 2010).

Aim of paper

The present work is part of an ongoing project on *Cities of Forces for Good* (CFG), which envisions cities, complex as they are, growing whilst nourishing their surroundings (Crutzen et al. 2007; Beck et al. 2010). Addressing environmental issues in a comprehensive way must consider more than one socio-economic sector and include the several interactions amongst them (Lundin et al. 2000). For instance, the water, energy, and food industries have been found to be relevant in the discussion of bio-fuels from poultry litter, demonstrating that the synergy amongst sectors is not always evident until innovative approaches are adopted (Barczak et al. 2005).

This paper describes a Substance Flow Analysis (SFA) in a multi-sectoral configuration. The vital cycles—represented by flows of nutrients (in the form of elemental N, P, and C), water, and energy—are studied as they enter, exit, and are transformed within an urban-rural system in which five socio-economic sectors are considered: water, energy, food, forestry, and waste management. The purpose is to gain an understanding of which are the key fluxes in terms of their magnitude and which sector(s) is(are) the most dominant for a certain substance. Exploring the interactions between seemingly disparate industrial sectors can result in solutions such as the creation of eco-industrial networks (Côté et al. 2006). The multi-sectoral character of the analysis also seeks to reveal the ramifications and implications of a change (structural or operational) in one sector for other sectors. This could be important for identifying prospective business opportunities.

This application of MSA is illustrated by a case study examining the Upper Chattahoochee Watershed (UCW) in north-east Georgia, USA. In addition to identifying major flows and the sectors responsible for these flows, the rural-urban characteristics of the UCW are seen as an opportunity for gaining insight into the interaction between the city and surrounding agricultural activities, thus to reveal possible cross-benefits, as presented in the results section. The following section is dedicated to exploring a system-wide account of material flows and energy and its multi-sectoral implications. The MSA is intended inter alia to be informative, credible, and useful for decision-making, even in the face of poor-quality data and other sources of uncertainty. Handling such uncertainty is accommodated within the framework of a Regionalized Sensitivity Analysis, which is based in large part on the use of Monte Carlo simulation (Hornberger and Spear 1980; Spear and Hornberger 1980). The concluding section of the paper outlines the insights derived from our multi-sectoral approach, summarizing the specific results of the case study, and finally proposing a line of future work for using the MSA framework as a decision-support tool in understanding and managing the metabolism of complex systems.

Methodology

Substance flow analysis

SFA is employed to follow the paths of nitrogen, phosphorus, carbon, and water. Energy is also accounted for as the internal energy of material flows as well as flows of solar radiation and electricity. This methodology involves estimation of only the direct fluxes, not embodied flows, since the focus is on investigating the magnitude of material flows and stocks, from which to draw inferences about resource efficiency and the degree of resource circularity within the system.

If a material flow F^j is calculated, then the flow of the five *species* can be estimated from the following equation:

$$\mathrm{F}_k^j = \mathrm{F}^j \cdot \mathrm{C}_k^j \tag{1}$$

where F_k^j is the flow of species k as part of the jth flow; C_k^j is the content of substance or species $k = 1, 2, 3, 4, 5$ (water, nitrogen, phosphorus, carbon, and energy, respectively) in the jth flow, generally as a mass fraction, or as energy per unit of mass (e.g. kWh t^{-1}) in the case of energy. This equation is particularly important for input flows, since other flows are typically estimated from mass and energy balances together with process modeling. Once flows are calculated, they are categorized as *resources* (useful inputs in the form of raw material or finished products), *products* (useful outputs that can be used by other systems), *air emissions* (net flux of materials in gaseous or aerosol form), *water emissions* (discharges to surface and underground water bodies), and *wastes* (materials disposed of in landfills). This categorization allows for a better identification of which flows are in contact with the environment and of the availability of the flow for further use.

The multi-sectoral model

Using SFA requires a certain structure to facilitate the definition of paths the substances go through once they enter the system under study. In the present work, this is achieved by implementing a systems analysis approach, which includes specifying the system's boundary, sub-systems, processes, and the connections among processes. The result of the analysis is then represented by a collection of flow diagrams developed for each sector involved. The flow diagrams serve as the blueprint for developing the mathematical expressions representing processes and the corresponding interconnections of material and energy flows. The equations, mainly mass and energy balances, involve a large number of parameters defining process rates, partition coefficients, and the overall behavior of the system. The specific values of these parameters depend on population consumption patterns, management choices, and process kinetics. The behavior of the system is also subject to forcing functions and input data, such as climate conditions and regional attributes (e.g. land use). The model is coded in MATLAB®, making the MSA model an adaptable tool that can be adjusted to region-specific conditions, expanded to include new processes, as well as being easily used for transient simulation of the system (Villarroel Walker 2010).

The water sector

Within the context of the MSA, the water sector is constituted by four main processes: water withdrawals and supply, sewage handling and treatment, atmospheric processes, and hydrological processes. Figure 1, built upon the urban water system described by Beck (2005) and Mitchell et al. (2001), to include also hydrological processes of urban and rural areas, shows the different components of the water sector and how these are physically connected. The overall water balance of the system can be summarized by Eq. 2, based on Mitchell et al. (2008):

$$W_{pp} + W_{wd} + I_{fw} + I_{ww} = W_{et} + W_{ds} + W_{ro} + W_{si} + \Delta S_w \tag{2}$$

The terms on the left-hand side of Eq. 2 express the net water inflow to the system, in which precipitation (W_{pp}) enters the control volume from the atmosphere and water

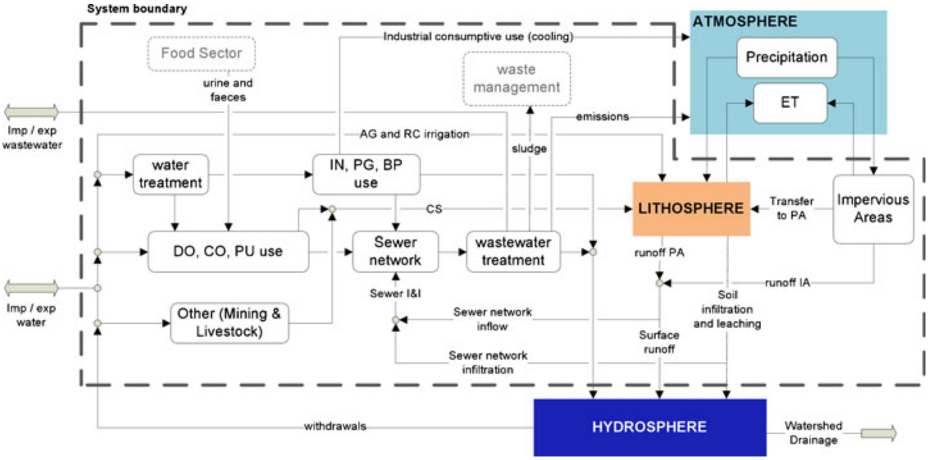

Fig. 1 Detailed flow diagram of the water sector. *Dashed-border boxes* denote other systems that receive or deliver flows from or to the present system. *DO* domestic or residential; *CO* commercial; *CS* consumptive use (including septic tanks); *PU* public; *PG* power generation; *BP* biofuel production; *IN* industrial; *ET* evapotranspiration; *PA* pervious areas; *IA* impervious areas; *AG* agricultural; *RC* recreational

withdrawals (W_{wd}) are water pumped from surface or ground water sources to satisfy domestic (household), commercial, industrial, public use, and power generation needs. Inter-basin transfers (at the watershed level) of finished water (I_{fw}) and wastewater (I_{ww}) are the net flux of water or wastewater exchanged with other basins. The right-hand side of Eq. 2 accounts for those flows that exit the system in the form of: discharges from municipal and industrial users to surface water streams or lakes (W_{ds}), evapotranspiration (W_{et}), surface runoff (W_{ro}), and water infiltrated through soil (W_{si}). The difference between inflows and outflows results in the storage of water within the control volume (ΔS_w).

Generally, once precipitation hits the ground it follows three paths: evapotranspiration, surface runoff, and infiltration. Water losses to the atmosphere via evapotranspiration (W_{et}) include plant transpiration, evaporation from surface water, evaporation from soil water, industrial evaporation, and evaporation of water stored in impervious surfaces after precipitation events. Therefore, W_{et} largely depends on land cover type, land use, and climatological conditions. In its present form, the MSA methodology classifies land cover into low intensity urban, high intensity urban, crop and pastures, open water and wetland, clear cut and sparse, and forested areas. For open water surfaces, and relatively humid pervious areas, the semi-empirical method of Penman can be used to estimate evapotranspiration (Dunne and Leopold 1978; Doyle 1990).

The difference between water withdrawals (W_{wd}) and discharges (W_{ds}) is regarded as consumptive water use. From the point of view of a watershed, this is typically defined as the water that is not returned to its source. In general terms, consumptive use refers to discharges to septic tanks, land application of wastewater effluent, outdoor watering of gardens and recreational areas, agricultural irrigation, interbasin transfers, and evaporation from industrial or power-generation use. For instance, the consumptive water use of a once-through cooling system of a typical thermoelectric plant due to evaporation is about 0.5×10^3 m^3 kWh^{-1} (Feeley et al. 2008). Additionally, the US Geological Service releases specific data on a regular basis with regard to water use, including consumptive use by different users (Hutson et al. 2005; USGS 2009).

As suggested by Fig. 1, the water sector is not only limited to fluxes of water. Hydrological processes such as soil infiltration (W_{si}) and surface runoff (W_{ro}) can contribute significantly to the transportation of nutrients, which is highly dependent on the nutrients made available by applied fertilizer and organic matter in the O horizon (Currie et al. 2003; Simmelsgaard 1998; Johnes 1996). Water is typically used as a medium for conveying household and industrial waste, which makes necessary its treatment—by wastewater treatment plants—before being discharged to a nearby water source. Municipal wastewater is collected by the sewer system which is usually affected by infiltration of groundwater and inflow from surface water runoff. Wastewater treatment, as part of the MSA, is handled as a single process unit using an advanced activated sludge treatment scheme. The amount of N losses to the atmosphere due to biological removal of N can be assumed to be proportional to the influent N (Sonesson et al. 2004) and, based on a typical plant-wide removal rate, e.g., 85–90% of influent, it is possible to estimate the nitrogen associated with sewage sludge. Since phosphorus has no gaseous phase, plant-wide P removal, typically about 95%, is sufficient for estimating the phosphorus recovered in sewage sludge as well. The flow path of carbon is more complex. For this, it is necessary to model the reduction of Biochemical Oxygen Demand (BOD), cell formation, and cell endogenous decay. These processes are modeled using equations for designing wastewater treatment plants as described by Reynolds and Richards (1977). In this way, the amount of carbon released as CO_2 in the activated sludge process can be estimated based on the atmospheric oxygen usage, as well as the suspended solids sent for digestion in the Waste Management sector (WMS).

Forestry and food sectors

These two sectors have similar behavior in the sense that most of their activity takes place in the soil environment before being sent to consumers. Figures 2 and 3 show the processes that are being considered and the flows interconnecting them. Carbon cycling processes—associated with biomass—are estimated based on the recommendations set out by IPCC (2006a), which account for different types of land use, including forests, grassland, and cropland. In forest and cropland, the C drawn into organic mass is reflected in the increase of C stocks in above-ground and below-ground biomass as shown in Eq. 3 below. Other flows that enter the forestry sector are associated with the import of wood products, such as paper, cardboard, lumber, and firewood. Outputs can be characterized by the CO_2 released from dead organic matter (DOM) and soil organic matter (SOM), and harvested wood products that are exported to other systems. Logging residue can be sent to the Waste Management sector for further processing or left on-site, in which case plant nutrients are mineralized, leached, or released to the atmosphere (e.g. CO_2 and N_2). For instance, in the particular case of C, this becomes part of the soil carbon pool with the potential for accumulation or release as CO_2. Thus,

$$\Delta C = \mathrm{A} \cdot G_w \cdot (1 + R_{ab}) \cdot C_{\mathrm{fract}} \tag{3}$$

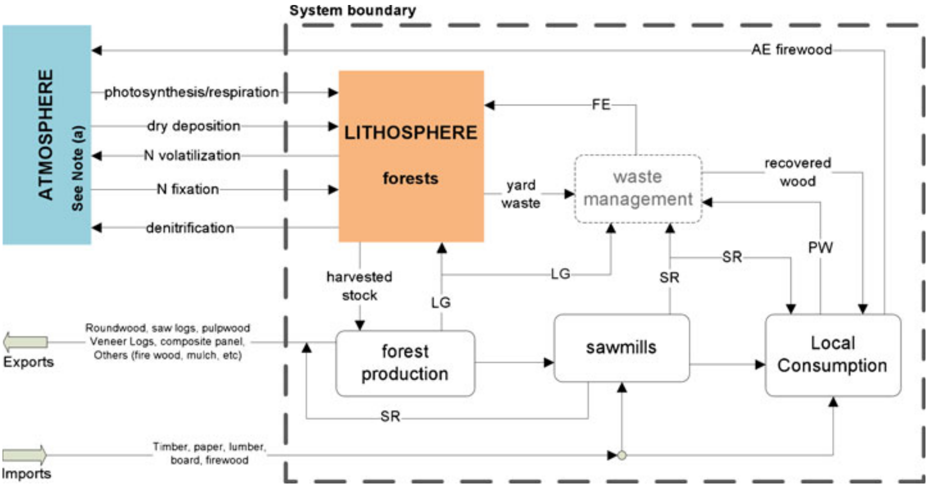

Fig. 2 Detailed flow diagram of the forestry sector. *Dashed-border boxes* denote other systems that receive or deliver flows from or to the present system. *LG* logging residue; *FE* fertilizers; *AE* air emissions; *SR* sawmill residue. (**a**) Flows between the lithosphere and the atmosphere, such as plant respiration and photosynthesis, N volatilization, denitrification, deposition, and N fixation, include those flows corresponding to the food sector (see Fig. 3)

where ΔC is the change in carbon stock; A is the area of interest; G_w is the average annual above-ground biomass growth; R_{ab} is the ratio of below-ground to above-ground biomass; C_{fract} is the mass fraction of carbon, typically 0.4–0.5. Within the

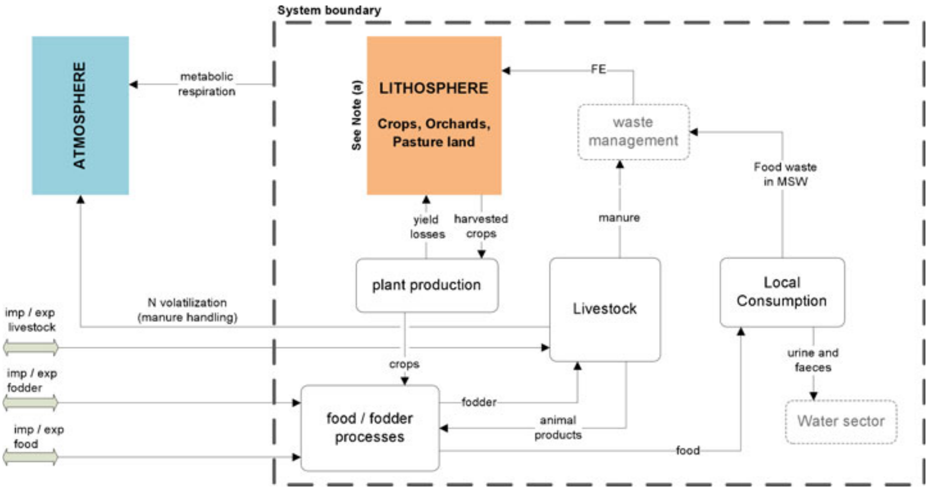

Fig. 3 Detailed flow diagram of the food sector. *Dashed-border boxes* denote other systems that receive or deliver flows from or to the present system. *FE* fertilizers; *MSW* municipal solid waste; *PW* paper and wood. (**a**) Flows between the lithosphere and the atmosphere, such as plant respiration and photosynthesis, N volatilization, denitrification, deposition, and N fixation, are all aggregated as part of the forestry sector in Fig. 2

forestry sector there are three main units considered: forest production, internal wood processing (depicted as *sawmills*), and local consumption. The internal use of wood products can be grouped into timber, firewood, and pulpwood products. In 2000, the average consumption per capita in the US was 2.0, 0.2, and 0.67 m^3, respectively (Howard 2007). Waste wood products are sent to the Waste Management system for recovery or disposal. About 44–50% of the municipal solid waste (MSW) generated is associated with wood products and biomass such as paper, yard trimmings, and construction materials (RWBECK 2005; EPA 2010).

The estimation of required fertilizers for the three types of representative land uses, i.e. grass, crop, forest, is based on regional or national data (Reicher and Throssell 1998; Landry et al. 2002; USDA 2008). The predominant or a representative group of plants being grown in the region of interest is considered for selecting the level of nutrient application. There are several practices for providing additional nutrients to soil, but they can be aggregated into two groups: (i) inorganic fertilizers, chemically synthesized; and (ii) organic fertilizers, such as treated sewage sludge, poultry litter, and manure from cattle and swine. When organic matter is utilized as a source of nutrients for crops or forests, particularly of N and P, the availability of these nutrients for plant intake needs to be considered for the calculation of the amount of manure to be applied. More specifically, this refers to *Plant Available Nitrogen* (PAN) and *Plant Available Phosphorus* (PAP). Manure handling and/or treatment have a significant influence on the C/N ratio, which regulates PAN. Fresh organic material typically shows higher PAN values than composted material (Gale et al. 2006). Fresh poultry litter can reach a PAN of 60%, with an average of about 30%, but after composting nitrogen will not be available at a rate higher than 10% (Gale et al. 2006; Preusch et al. 2002; Tyson and Cabrera 1993). PAP, on the other hand, is usually higher than PAN with respect to the total content of the nutrient in manure. P losses in organic fertilizer are mostly attributed to runoff and leachate during handling, such as composting, for instance (Eghball et al. 1997). PAP has been found to be about 70% for poultry litter (Eghball et al. 2005) and sludge applications (Lundin et al. 2004).

Besides the C drawn into the food sector due to organic material growth, there are flows of food and fodder entering or exiting the food sector. Food has been classified into representative groups as a way to organize the food categories reported by the Food and Agriculture Organization of the United Nations (FAO). With the help of data such as those presented in Table 1, which shows consumption patterns in the US for the year 2000 (FAO 2009), it is possible to estimate flows of food imported or exported from the system. Food waste, typically 10–14% of the municipal solid waste (MSW) in the US (EPA 2010), is sent to the Waste Management sector.

Table 1 Average food consumption per capita in the US for the year 2000

Food group	Consumption ($kg\ y^{-1}\ cap^{-1}$)
Fruits	125
Cereals	116
Vegetables	207
Meat (bovine, swine, poultry)	121
Fish/Seafood (seafood, freshwater fish)	23
Dairy (milk, butter, ghee, eggs)	272
Others[a]	206

[a] Includes alcoholic beverages, vegetable oil, stimulants, sugar, and sweeteners

Feed consumption by livestock, which defines the amount of fodder imported or exported, is based on animal inventory and digestible energy (DE) requirements, usually estimated in kcal d^{-1} per head, as recommended by NRC (1987). DE determines the amount of dry mass fed to livestock (e.g. corn and hay). Additional nutrient supplements are usually necessary to comply with specific requirements for minerals (e.g. phosphorus) and additional protein, which is the largest nitrogen contributor in food (NRC 1961, 1998, 2000). Metabolic respiration of livestock, and humans too, is often ignored. However, Prairie and Duarte (2007) report that an estimated global 0.6 Gt C y^{-1} are associated with human respiration, and 1.5 Gt C y^{-1} with livestock. Metabolic respiration is typically calculated from allometric relations (Prairie and Duarte 2007).

In natural ecosystems, there are two processes that return nitrogen to the atmosphere: denitrification and volatilization. The first is mostly a biological process mediated by bacterial activity that releases N_2 and, in smaller quantities, N_2O. The ratio N_2:N_2O, typically equal to 16, depends on how well the field is drained (moisture), temperature, moisture, and availability of food (carbon). In cropland the type and amount of fertilizer applied, together with irrigation, has a strong influence over denitrification (Sánchez et al. 2001; Dowdell and Mian 1982). In forests, almost 70% of the denitrification process takes place within the upper soil layer (0–10 cm) and it is in the same forest floor where nitrification occurs, to account for about 75% of all the nitrogen input to forest watersheds (Todd et al. 1975). Volatilization on the other hand, is a release mostly in the form of ammonia (NH_3) and nitrogen oxide (NO_x) gases from organic and inorganic sources, e.g. fertilizers, manure, decaying plant material. The phenomenon takes place in fertilizer land application and manure handling and storage. Nitrogen losses, estimated as the difference between fresh manure and land applied manure, are about 35% for poultry litter, 25% for anaerobic pits, 60% for oxidation ditches, and 80% for lagoons, with the last three practices relevant for cattle and swine manure handling (Risse 2009). Nitrogen volatilization from fertilization is typically in the range of 3–30% for inorganic fertilizer and 5–50% for organic sources of nutrient (IPCC 2006a). Depending on the nitrogen species, between 40 and 80% of global nitrogen emissions to the atmosphere are related to human activities. The fixation of nitrogen has also been greatly influenced by human activity. Anthropogenic N fixation, mainly due to fertilizer production ($\approx$80 Gt N y^{-1}), has almost doubled the total amount of nitrogen captured into biologically available pools compared to the fixation in terrestrial ecosystems prior to extensive human activity, 90–140 Gt N y^{-1} (Vitousek et al. 1997).

Energy sector

Energy balances at the urban level have been made mainly from two perspectives: climate (Mitchell et al. 2008) and energy use (Kaye et al. 2006; Hosier 1993). The former considers natural (solar) and anthropogenic (heat released) energy fluxes as a way to gain insight into how these fluxes affect the water cycle, as in Eq. 4.

$$Q^* + Q_F = Q_E + Q_H + Q_W + \Delta Q_S \tag{4}$$

where Q^* is the net all-wave radiation; Q_F is the anthropogenic heat flux; Q_H is the turbulent sensible heat flux; Q_E is the latent heat flux; and ΔQ_S is the net heat storage; Q_W is the heat lost via runoff and aquatic emissions.

The second perspective focuses on the use of renewable and non-renewable energy sources and what are the drivers for such consumption. The MSA couples both approaches, since together they can reveal information about how efficiently the rural-urban system uses available energy sources, including from the sun. The MSA includes the climate-oriented model described by Mitchell et al. (2008) and Grimmond and Oke (2002). The energy balance accounting for power generation and fuels is described in Fig. 4.

As of 2009, the US's primary energy consumption was about 27.6 PWh, of which nearly 83% was satisfied by fossil fuels (coal, petroleum, and natural gas), 9% from nuclear fuels, and the remaining 8% included biomass, hydropower, solar, wind, and other alternative energy sources (EIA 2010). End-users of fuels or electricity can be classified into various activities: domestic, commercial, industrial, and transportation. By 2008, 40% of households in the US relied mostly on electricity, while 60% used a combination of electricity and natural gas, in a ratio near 50:50 (EIA 2011). A less significant fuel demand at the residential level is that of firewood, with a US average of firewood consumption of some 0.2 m^3 per capita (Howard 2007). The commercial sector uses electricity, natural gas, and biomass. The industrial sector adds coal to its sources, besides electricity, natural gas, and biomass. Transportation, on the other hand, is mainly based on gasoline, diesel, and natural gas. Indirectly, the Waste Management sector can generate heat or electricity from processes such as the incineration of MSW and the capture of landfill gas. The MSA model accounts for the flow of fuels as materials based on the requirements of the system, usually expressed as the amount of energy (kWh) required to accomplish an activity. The next step is to establish the energy source for each type of activity. Converting an

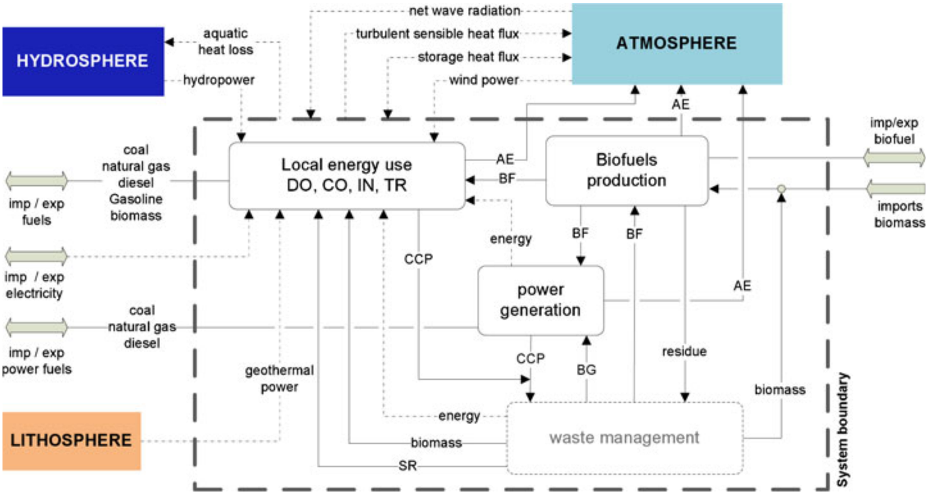

Fig. 4 Detailed flow diagram of the energy sector. The *dotted* line (. . . .) represents an energy flow with no mass value. *Dashed-border boxes* denote other systems that receive or deliver flows from or to the present system. *AE* air emissions; *DO* domestic or residential; *CO* commercial; *IN* industrial; *TR* transportation; *BF* liquid biofuel; *BG* biogas; *CCP* coal combustion products; *SR* sawmill residue

energy source into available work is associated with the level of efficiency of the different processes involved, from generation to distribution. For example, a power plant will need to generate 107 MWh to effectively deliver 100 MWh at the user site, due to transmission and distribution losses, which are about 7% in the US. If the generation is coal-powered, the mass of coal required is about 34 tonnes, assuming that coal has an energy value of 9 MWh t^{-1} and the process efficiency is 35%.

A part of the energy sector model deals with the estimation of emissions from the different types of fuels. For liquid and gaseous fuels this is more or less straightforward and 100% oxidation is assumed (IPCC 2006b). A slightly more complex approach is required for biomass and coal. Biomass, assumed to have typical wood properties, has an ash content of between 0.75 and 2.5% (FAO 1986) and a portion of the biomass nutrient content remains in the ash, particularly minerals such as P. Based on an ultimate analysis of coal combustion residue, Hower et al. (2005) report less than 3% of carbon in bottom ash and boiler slag. These two by-products, plus fly ash and flue gas desulfurization (FDG) material, are usually called *Coal Combustion Products* (CCP) and are produced at a rate of nearly 33 kg per 100 kg of coal burnt (Butalia et al. 1999). Since coal represents more than 37% of the overall US demand for primary energy (EIA 2010), CCP should not be ignored. Most of the coal-bound phosphorus remains in CCP, while the rest is released to the atmosphere as particulate matter. The particulate matter is released at a rate of 4–110 mg per kWh generated (Ohlström et al. 2000), of which about 0.5–1% is phosphorus (Mahowald et al. 2008). The mechanisms by which coal combustion releases nitrogen species are more complex. NO_x emissions from coal combustion depend on the nitrogen content of coal, usually between 0.6 and 2.3% dry ash-free (Kambara et al. 1995), but only 75% to 90% is associated with the fuel-bound nitrogen, while the rest is provided by oxidation of combustion air. N mass loss in coal combustion is proportional to the overall coal mass loss (on a dry ash-free basis) but smaller by a factor of 1.25–1.50 (Baxter et al. 1996). The burning of fossil fuels has significant influence on the global N cycle, since it releases long-term fixed N to the atmosphere at a rate larger than 20 Gt N y^{-1} (Vitousek et al. 1997).

Waste management sector

The waste generated in all the previous sectors is handled in the Waste Management sector (WMS) as the ultimate barrier between human activities and the environment. As shown in Fig. 5, this sector is the most complex of all due to the various process-intensive units involved, with a total of four: sludge digestion, solid waste incineration, composting, MSW landfilling. The underlying purpose of the structure of the WMS is: recovering energy and recovering material with a fertilizer value.

The inputs to this sector are municipal solid wastes (MSW), wastes generated from the wastewater treatment process, manure from livestock operations, yard waste, and CCP from coal-powered plants. MSW is the largest component, with a generation rate of 1.2–2.5 kg d^{-1} per capita (Arena et al. 2003; RWBECK 2005), but this varies enormously among regions. The variability is also evident in the composition of the MSW.

The MSW incineration process is used as a way to convert waste into energy. A typical MSW incineration unit will release 0.7–1.2 tonnes of carbon dioxide (CO_2),

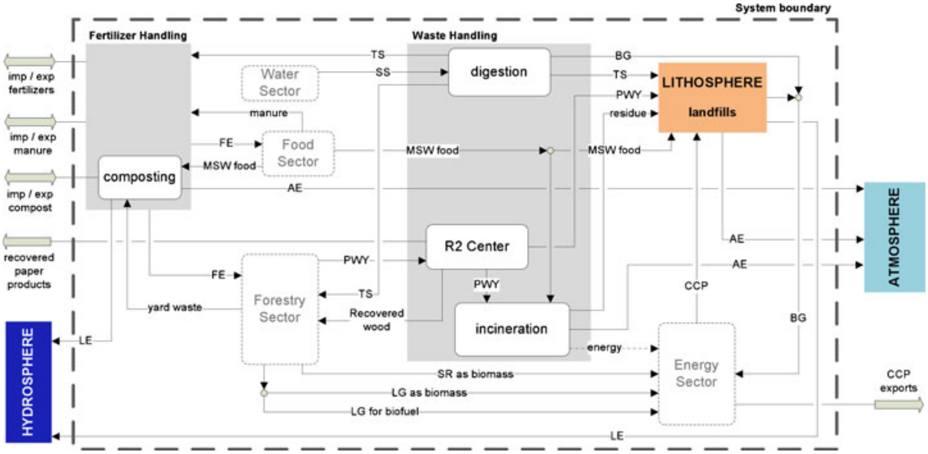

Fig. 5 Detailed flow diagram of the waste management sector. *Dashed-border boxes* denote other systems that receive or deliver flows from or to the present system. *BF* liquid biofuel; *BG* biogas; *AE* air emissions; *MSW* municipal solid waste; *R2* recycling and reusing; *TS* treated municipal sludge; *SS* fresh municipal sludge; *SR* sawmill residue; *FE* fertilizers; *LG* logging residue; *LE* leaching; *CCP* coal combustion products; *PWY* paper, wood, and yard waste

with a corresponding generation of 300–600 KWh, per tonne of waste. This figure makes no distinction between biogenic and fossil carbon, the latter being 33–50% of the total C released (Johnke 2000). The portion of MSW considered by the MSA model includes only food, wood products, and yard residue, thus the emission of gases and the generation of energy is calculated with considerations similar to those of biomass combustion. The energy produced depends on the energy content of the materials incinerated and the process efficiency.

Municipal sludge digestion seeks to reduce the solid mass weight and pathogen activity by oxidation of degradable organic material. The process is carried out by microbes under very specific process conditions of temperature and oxygen availability. The digestion process considered in this work is a thermophilic reactor under anaerobic conditions, which can be summarized by the following chemical expression,

$$\mathrm{OM} + \mathrm{Oxygen} \xrightarrow{\text{Anaerobic microbes}} Cells + E + \mathrm{CH_4} + \mathrm{CO_2} + Others \tag{5}$$

where OM is organic matter and E is energy for cells. Oxygen is mainly provided by radicals such as carbonates ($\mathrm{CO_3^{-2}}$), nitrates ($\mathrm{NO_3^{-1}}$), sulphates ($\mathrm{SO_3^{-1}}$) and phosphates ($\mathrm{PO_4^{-3}}$); *Others* refers to traces of $\mathrm{N_2}$, $\mathrm{H_2S}$, and water vapor. Typically 50–75% of the volatile organic matter in sludge, which corresponds to 65–75% of the total amount of solids, is destroyed by the digestion process, resulting in the production of $\mathrm{CH_4}$ and $\mathrm{CO_2}$ in a proportion that varies with the performance of the microbes, but is normally in the 1.2–3.0 range of $\mathrm{CH_4{:}CO_2}$. Gas production rate ranges from 1.05 to 1.75 kg per kg of volatile solids degraded (Reynolds and

Richards 1977), with a heating value calculated as a function of the volume of CH_4 characterized by having 10.34 kWh m^{-3} at standard conditions.

Another waste handling practice is composting. Manure, discarded food, and yard waste are the typical feed for composting. The result is a stable material, with no nuisance odors, no disease vector attraction, and no pathogens, but with still some nutrient value. The efficiency of the composting process depends on the C to N ratio (ideally 10–30) and humidity (50% desirable). Partition factors, estimated from previous studies (Eghball et al. 1997; Tiquia et al. 2002; Hao et al. 2004), are used to calculate the mass of nutrients lost via leaching and air emissions, typically about 60, 40, and 15% for C, N, and P respectively.

Similar to the composting process, landfilling involves the decomposition of material and releases of nutrients to the water table and atmosphere. The model assumes that 100% of the leaching produced is lost through the soil and that a portion of the gas is captured for energy purposes. Under simulated conditions, Raveh and Avnimelech (1979) elaborated a set of empirical equations for the estimation of C and N concentrations in leachate over time. The data generated by Scott et al. (2005) can be adapted to estimate the leaching of phosphorus. The calculation of gaseous emissions from a landfill is based on the LandGEM model developed by Alexander et al. (2005) for the USEPA. This method calculates the amount of CH_4 based on: (i) the mass of waste (tonnes), (ii) a methane generation rate (y^{-1}), (iii) and a value of potential methane generation ($m^3\ t^{-1}$). Once the amount of CH_4 has been estimated, it is possible to estimate the total amount of carbon ($CH_4 + CO_2$) and nitrogen by using a typical composition of landfill gas, usually 44–53% CH_4, 34–47% CO_2, and 4–20% N_2 in the US (Scott et al. 2005).

Uncertainty management

One the purposes of the MSA framework is to provide useful information for decision makers and policy formulation; another is its prospective use for the evaluation of future scenarios and transitions toward desirable states or policy objectives. For this, it is critical that the framework involves a quantitative procedure to account for the uncertainty of the results generated (Beck et al. 2009). The uncertainty introduced into the model—via parameters and inputs as the result of measurement errors, instrument errors, or simply random errors—is handled by one of the features of the Regionalized Sensitivity Analysis (RSA) procedure. RSA performs a *Monte Carlo* simulation across the parameter space, generating possible model output values which can later be analyzed and interpreted, while uncertainty propagation is being considered. More detailed explanation of the procedure with regard to the uses and the mathematical background of the RSA can be found elsewhere (Osidele et al. 2003; Villarroel Walker 2010). Information about the uncertainty attached to data is sometimes available, but its absence is more commonly the case. Previous SFA studies have proposed a set of uncertainty levels, expressed as interval factors in the form $\{*/u_j\}$, based on the quality and the applicability of different sources of information (Danius and Burström 2001; Hedbrant and Sörme 2001). For instance, data collected specifically for the region under study has less uncertainty compared with national or global averages, so if a factor of $u_j = 2$ is used, then the parameter space is defined by $[\frac{1}{2}\overline{\alpha}_j, 2\overline{\alpha}_j]$, where $\overline{\alpha}_j$ is the most likely value of the jth parameter α_j.

Data collection

As for methods such as Life Cycle Assessment (LCA), the MSA involves generating an inventory of materials and energy. This requires an extensive volume of data, which on many occasions are heterogeneous, in the sense that sources of information are numerous, the formats of data are quite variable, and data are not always available at the right scale or for the specific geographic location where the study is being undertaken. The magnitude of material flows varies significantly from one region to another, but reliable information can nevertheless be retrieved from regional and national agencies, extension agencies reports, and peer-reviewed journal articles. Energy data can be obtained from the Energy Information Agency (EIA), food and crop data from the US Department of Agriculture (USDA) and Food and Agriculture Organization of the United Nations (FAO), environmental information from the US Environmental Protection Agency (USEPA), the US Geological Service (USGS), or the Intergovernmental Panel on Climate Change (IPCC).

Case study: The Upper Chattahoochee Watershed

The capabilities of MSA are illustrated in the context of the Upper Chattahoochee Watershed (UCW) located in north-central Georgia, in the south-eastern USA (see Fig. 6). Nearly a quarter of the Metropolitan Atlanta area is within this watershed. In 2000, the population of the Upper Chattahoochee Watershed was about 1.3 million. The major surface water storage in Georgia, Lake Sidney Lanier, is located just to the north of Atlanta, within the limits of the UCW. The lake is also the principal source of drinking water for the metropolitan Atlanta area. The watershed area, a

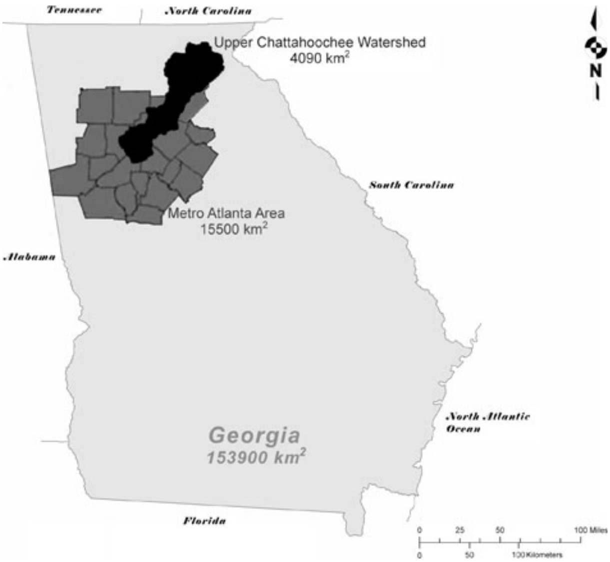

Fig. 6 Geographical location of the Upper Chattahoochee Watershed within the state of Georgia, USA

total of 4093 km^2, is comprised of the Appalachian Mountains to the north, and low to high intensity urban areas to the south. It has a variety of land uses including significant poultry production and silviculture. In 2000, land cover was categorized as follows: open water 4%, forest 53%, urban and sub-urban 29%, pasture and crops 10%, other 4% (NARSAL 2006). The large proportion of forested area indicates that silvicultural activities are prominent. Estimates derived from reports by Thompson (1998) indicate that the annual growth-rate of softwood and hardwood within the watershed are about 3.7 and 4.5 m^3 ha^{-1} y^{-1} respectively. Removal rates are estimated as 5.8 m^3 ha^{-1} y^{-1} for softwood and 2.9 for hardwood.

About 88% of the Upper Chattahoochee Watershed is located in the Piedmont area and only 12% in the Blue Ridge. With a moist and temperate climate, the UCW receives an annual average of 1270 mm of precipitation, primarily during the winter and early spring. The average monthly temperature in the Metropolitan Atlanta area ranges from about 7 to 26°C (Chapman and Peck 1997). It is important to have a sense of the hydrological characteristics of the UCW, such as typical river discharge and baseflow, so that the range assumed for the parameters used for calculating surface runoff are within the correct order of magnitude. The mean unit-area baseflow has been estimated as 0.016 m^3 s^{-1} km^{-2}, while the mean annual baseflow in the Chattahoochee River is about 69–82% of mean annual stream discharge (Chapman and Peck 1997).

Although more than 50% of the UCW area is forested, human interventions in the watershed's water cycle are not insignificant, with over 500 National Pollutant Discharge Elimination System (NPDES) facilities. Consumptive use of water is an important component of water withdrawal. For instance, about 5.7 m^3 s^{-1} (130 million US gallons per day) have been reported as the net inter-basin transfer of finished water from the portion of the Chattahoochee Watershed located within the Metropolitan North Georgia Water Planning District (JJG 2003b). Similarly, over 1.7 m^3 s^{-1} (40 million US gallons per day) of wastewater from other basins were treated in the Chattahoochee Watershed. Wastewater treatment is simulated according to the known concentration of sewage entering the R.M. Clayton plant (as typical), the major wastewater treatment facility in the watershed (Mines et al. 2004; Emmerth and Bayne 1996). In the same region, approximately 17% of the wastewater generated is handled by septic systems, varying significantly from county to county as a function of population. In more populated counties such as Fulton County and Dekalb County, about 10% of households use septic tanks, whereas in northern areas, e.g., Habersham County, septic systems can be found in 40–90% of the households (JJG 2003b). The percentage of population discharging to septic systems in the northern region of Georgia, has been found to follow the expression $87.4 \cdot e^{-0.83 \cdot \rho}$ where ρ is population per acre (JJG 2003a).

By 2005, the total energy demand in the state of Georgia was about 0.9 PWh, distributed among different activities: domestic, commercial, industrial, and transportation, with proportions of 24, 18, 29, and 29% respectively (GAEPD 2006). The 2007 EIA Energy Report for Georgia provides information on individual monthly consumption by domestic, commercial, and industrial users of electricity. Based on this, and considering the state's population, it is possible to estimate a value of consumption per capita, which results in 5.9, 4.9, and 3.6 MWh y^{-1} for domestic, commercial, and industrial purposes, respectively. Electricity generation within the UCW is based on three processes: thermoelectric coal plant, thermoelectric natural gas plant, and hydrolectric. The McDonough Power Plant, operated by Georgia Power, has been migrating from its original coal-only based generation to natural gas and has a current combined generation (coal and natural gas) capacity of about 568 MW or 4975 GWh y^{-1}. Hydroelectric power is being generated from two dams, Morgan Falls with a currently nominal capacity of 16.8 MW, which results in circa 145 GWh y^{-1}, and Buford Dam with about 100 MW of generation capacity, which enables the delivery of nearly 870 GWh y^{-1} (JJG 2000). Morgan Falls, built in 1904, regulates the Bull Sluice Reservoir, which has a full pond surface area of 2.7 km^2 and is licensed to Georgia Power (GAPOWER 2011a). Buford Dam, finished in 1956, impounds Lake Sidney Lanier, with its surface area of 150 km^2 at full capacity, and is currently operated by the US Army Corps of Engineers.

An important driver of the watershed economy is the livestock industry, represented to a large extent by the production of poultry. Based on data released by USDA (2004), the estimated inventory of poultry birds in 2000 was 23 million heads, while for cattle and swine this was 60 and 20 thousand heads respectively.

Results and discussion

Water

The predominant flows of water are associated with climate and natural processes. Precipitation enters the system at a rate of 147.2 $m^3\ s^{-1}$, of which 64% is returned to the atmosphere by evapotranspiration. Calculated soil infiltration is about 24% of the amount received as rainfall, leaving nearly 12%, or 13.4 $m^3\ s^{-1}$, for surface runoff from pervious and impervious areas. Although the latter constitutes only 10% of the total watershed area, it contributes nearly 68% of the total surface runoff that reaches the Chattahoochee River. Table 2 shows the largest water flows, after precipitation and evapotranspiration, in terms of their volumetric flow and includes the estimated standard deviation as a percentage of the mean value. Human-manipulated water flows are predominantly found in the water sector, i.e., water supply and wastewater treatment, and the energy sector. Over 50% of the total water withdrawals (F_1^3) is utilized for power generation and nearly 20% is exported to other basins, while the rest goes to internal use. Inter-basin transfer may seem high, but it reflects the loss of storage volume from Lake Lanier: a loss of over 2 m of water level, accentuated by the drought of 2000. Water withdrawals for drinking water supply for domestic, commercial, public, and industrial uses are 9 $m^3\ s^{-1}$, of which about 56% is for residential purposes. Also evident in Table 2, the highest levels of uncertainty (18.6 and 13.6%) are found to be associated with hydrological processes, suggesting that more specific information might be required to represent the heterogeneous hydrological characteristics of the watershed.

Water in rural-suburban-urban systems is typically not accumulated (Grimmond and Oke 1986), since hydrological processes balance each other and, in the case of human-manipulated flows, water withdrawals (F_1^3) are basically translated into returns to water sources (F_1^{93}), consumptive use (F_1^{94}), and interbasin transfers (F_1^{284}). The difference lies in the additional flow handled by the sewer system due to inflow and infiltration (F_1^{82}), in other words: $F_1^3 \approx F_1^{93} + F_1^{94} + F_1^{284} - F_1^{82}$.

Table 2 List of the most relevant water flows in the Upper Chattahoochee Watershed in the year 2000 and estimated standard deviation (s.d.)

Flow number[a]	Flow description	Mean value[d] (m^3 s^{-1})	s.d. (% of the mean)
F_1^{83}	Total soil infiltration	(36.6)	18.6
F_1^{3}	Total water withdrawals	+34.4	6.4
F_1^{93}	Total water returned to surface sources[c]	(29.9)	7.7
F_1^{295}	Surface runoff that reaches the river	(13.3)	13.6
F_1^{6}	Water withdrawals for public supply	8.8	6.2
F_1^{284}	Interbasin transfer of fresh water	(6.5)	5.8
F_1^{11}	Water use for domestic purposes	4.9	10.6
F_1^{82}	Inflow/Infiltration to sewer system	4.1	18.3
F_1^{19}	Water use for commercial purposes	2.1	5.7
F_1^{94}	Total consumptive use to soil[b]	1.9	4.9

[a] Refer to Eq. 1 for explanation of the designation of flow numbers and indexes

[b] Includes irrigation in agriculture, watering for domestic, commercial and public use, and water use for mining and livestock operations

[c] 62% from industrial and power generation facilities and 38% from municipal wastewater treatment plants

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

Nitrogen

Agriculture, represented by the poultry industry, and fuel consumption are responsible for the largest nitrogen flows, as shown in Table 3. The significance of the poultry industry in Georgia can be represented by the increase of the inventory of broiler and other meat-type chicken, which has almost doubled since 1990 to reach more than 230 million heads (USDA 1994, 2009). This is reflected in the largest flow of nitrogen associated with feed for livestock, F_1^{176}, of which only 3% is produced within the UCW. Poultry production accounts for 83% of the total use of feed. Consequently, manure generation is quite significant at 16,000 t N y^{-1}, 75% of which is from poultry operations, but as much as 5,400 t N y^{-1} of the nitrogen in poultry manure are lost due to volatilization during storage and handling. Most of the fertilization operations, e.g., for crops, pastures, recreation areas, and gardens, rely on imported inorganic sources (roughly 70% of the total nutrient applied, F_1^{139}), while the rest is supplied by organic sources such as poultry litter (25%) and treated municipal sludge (5%).

The use of fuels is second in overall importance for N flows, but it represents the largest emission to the atmosphere. Local fuel consumption, which includes domestic, commercial, industrial and transportation, is nearly 27,000 t N y^{-1}. Of these emissions, 55% are released by industrial operations, 29% from commercial, 13% by residential, and 3% from transportation, but 88% is due to the use of natural gas. Emissions from power generation are about 20,000 t N y^{-1}, of which 88% is associated with coal and 12% natural gas. Of the total amount of coal imported into the system, 26,500 t N y^{-1} (nearly 90%) is used for power generation purposes, while the rest is for industrial purposes. These two coal applications generate a total of

Table 3 List of the most relevant nitrogen flows in the Upper Chattahoochee Watershed in the year 2000 and estimated standard deviation (s.d.)

Flow number[a]	Flow description[b]	Mean value[c] (t N y^{-1})	s.d. (% of the mean)
F_2^{176}	Total feed consumption by livestock	27814	7.0
F_2^{232}	Emissions from local consumption[e]	(26883)	28.6
F_2^{218}	Emissions from power generation	(20233)	9.6
F_2^{139}	Total nutrient applied to soil for fertilization	13067	5.6
F_2^{96}	Wastewater to WWTPs (influent)	10039	26.0
F_2^{156}	Total food consumed	9488	3.5
F_2^{130}	Air emissions from WWTPs	(7023)	26.5
F_2^{271}	Material landfilled[d]	6917	9.1
F_2^{83}	Soil infiltration	(4151)	8.7
F_2^{295}	Surface runoff that reaches the river	(3623)	24.8

[a] Refer to Eq. 1 for explanation of the designation of flow numbers and indexes

[b] WWTP wastewater treatment plant

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

[d] Includes municipal sludge, refuse food, wood products, yard waste, municipal solid waste combustion residual, and CCP

[e] Includes domestic or residential, commercial, industrial, and transportation use

6,300 t N y^{-1} in coal combustion products (CCP); 65% of CCP is estimated to be landfilled.

Almost 90% of the food production in the system is based on meat production, i.e., 9,300 t N y^{-1}, a value comparable, in N terms, to the total food consumed of 9,500 t N y^{-1}. The ingestion of N, through the consumption of food, is 47% from meat (beef, pork, poultry), 27% from cereal products, while the rest is provided by vegetables and seafood (18%) and, to a lesser extent, fruits and dairy produce (4%). The intake of food results in the production of urine (5,000 t N y^{-1}), feces (1,400 t N y^{-1}), and about 1,100 t N y^{-1} as food refuse. That part of the first two of these that is not sent to septic tanks is collected, together with industrial discharges, in the sewer network (F_2^{96}) and processed by wastewater treatment plants (WWTP), where about 70% of the nitrogen is released to the atmosphere by denitrification. The remaining N is partitioned in more or less equal parts between the WWTP effluent discharged to water bodies and the co-produced municipal sludge.

Hydrological processes have a moderate significance for the system's N metabolism. Surface runoff transports a total of 3,600 t N y^{-1} to the Chattahoochee river, largely from impervious areas (70%). Wet deposition of nitrogen via precipitation, which accounts for 77% of total deposition, is about 3,200 t N y^{-1}. The total riverine export is about 10,400 t N y^{-1}, or 25 kg N y^{-1} per hectare, comparable to the values obtained by Boyer et al. (2002) for a similar region, i.e. 10% urban and 50% forested. Soil infiltration of N, which accounts for leaching from agricultural land, leaching from landfills, and septic tanks, results in 4,100 t N y^{-1}, which is larger than the nitrogen loss through runoff and consistent with the large proportion of pervious surface.

Table 4 Comparison of intensive system characteristics of nitrogen

	UCW (kg N y^{-1} cap^{-1})	Other studies (kg N y^{-1} cap^{-1})
N in household wastewater	2.7–7.2	5.2[a], 5.9[b]
Municipal organic waste	0.7–1.1	1.0[a]
Food consumption	6.8–7.8	6.5[a], 6.4[b], 6.8[c]
Refuse food (as a % of consumed food)	8–15%	14%[a]
Use of fodder	18–24	23[a]
NO_x and elementary N from fuels	23–57	30[a], 28[c]
N in WWTP effluent	0.4–1.9	1.5[b]
N fixation and deposition	3.3–7.4	4.5[c]

All values reported in (kg N y^{-1} cap^{-1})
[a] Source Antikainen (2007), case study developed for Finland in the 1990s
[b] Source Forkes (2007), scenario for the City of Toronto in year 2001
[c] Source Kaye et al. (2006), corresponding to the City of Phoenix in year 1995

Surprisingly, despite the regional importance of the forestry industry, wood-associated flows are not within the largest in the system. Tree harvesting produces effectively about 600 t N y^{-1}, after logging residue, while the total consumption of wood products including lumber, paper, and firewood is about 2,000 t N y^{-1}. Landfilled waste of wood-pulp products, e.g. paper and cardboard, amounts to 810 t N y^{-1}, while about 680 t N y^{-1} are recycled.

Table 3 also reveals the largest uncertainties of the system with regard to nitrogen, namely (a) the energy usage in activities other than power generation, (b) the composition of sewage, (c) emissions from wastewater treatment, and (d) the estimation of urban runoff. Finding that the food and the energy sectors are involved in the largest flows of N in the system is consistent with the results presented by Antikainen (2007). Numerical comparison with other systems can be achieved by using intensive characteristics, i.e., data reported per unit of area or population, as shown in Table 4. This kind of comparison allows the inference of similarities and differences among regions. For instance, one could say that the ingestion of proteins on a per capita basis, presumably from meat, is larger in the UCW compared to regions abroad such as Toronto and Finland, but more akin to the consumption in Phoenix.

Phosphorus

The largest flows of phosphorus are related to feed for livestock and fertilizer use, and to a lesser extent to fuel flows and hydrological processes (see Table 5). About 6,300 t P y^{-1} enter the system as feed, with 90% being dedicated to the poultry industry. Consequently, manure is generated at a rate of 4,100 t P y^{-1}, mostly from poultry operations (3,700 t P y^{-1}). In terms of P, 44% of the poultry litter produced is applied to soil as a fertilizer. Food produced reaches 2,100 t P y^{-1}, of which 92% is contained in meat products. Meat exports amount to 900 t P y^{-1}, suggesting that local meat production covers a significant portion of local consumption, which is 50% of the population diet. Cereal and dairy consumption are 21 and 13% respectively. Approximately 240 t P y^{-1} of the food consumed is returned as waste, and most is sent for landfilling, but this accounts only for 8% of the total material landfilled. Coal combustion products (CCP), of which 65% is landfilled (with the remainder finding

Table 5 List of the most relevant phosphorus flows in the Upper Chattahoochee Watershed in the year 2000 and estimated standard deviation (s.d.)

Flow number[a]	Flow description[b]	Mean value[c] (t P y^{-1})	s.d. (% of the mean)
F_3^{176}	Total feed consumption by livestock	6288	7.5
F_3^{139}	Total nutrient applied to soil for fertilization	3570	10.2
F_3^{271}	Material landfilled[d]	3216	26.8
F_3^{96}	Wastewater to WWTP (influent)	2063	33.8
F_3^{164}	Total food produced	2115	9.4
F_3^{156}	Total food consumed	2023	3.6
F_3^{233}	Imports of coal	+1938	58.2
F_3^{295}	Surface runoff that reaches the river (output)	(1242)	12.1
F_3^{83}	Total soil infiltration	(895)	26.1
F_3^{91}	Wastewater returns (effluent)	206	45.1

[a] Refer to Eq. 1 for explanation of the designation of flow numbers and indexes

[b] WWTP wastewater treatment plant

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

[d] Includes municipal sludge, refuse food, wood products, yard waste, municipal solid waste combustion residual, and CCP

an alternative use), are more significant, contributing 39% of the total phosphorus landfilled, while paper and wood products represent 14 and 12% of P respectively, even though nearly 46% of the paper waste generated is recovered before reaching the landfill. CCP generation accounts for practically all the P that enters the system as coal for power generation and industrial uses.

Based on the load of P in surface runoff (F_3^{295}) and the discharges from WWTPs (F_3^{91}), the Chattahoochee River exports are on average 1,400 t P y^{-1}, equivalent to 3.4 $\text{kg P y}^{-1}\ \text{ha}^{-1}$, where 85% is from non-point sources from agricultural land and urban areas. This figure seems relatively high compared to the study conducted by Emmerth and Bayne (1996) at Fairburn, GA, (also on the Chattahoochee River), which resulted in 1.6 $\text{kg P y}^{-1}\ \text{ha}^{-1}$. However, their results are associated with an average phosphorus concentration of 0.209 mg L^{-1} in river water versus the averaged concentration of 0.55 mg L^{-1} used in the MSA, which latter was obtained from the US Geological Service (USGS) sampling site No. 02336490 (Chattahoochee River at GA-280) near Atlanta. Infiltration through soil is also relevant, totaling nearly 900 t P y^{-1} from three main sources: (i) landfills (33%), (ii) septic tanks (16%), and (iii) the remainder from fertilizer applied to land. Atmospheric deposition of P, which is less relevant overall, is about 160 t P y^{-1}, predominantly from wet deposition (85%).

Table 5 offers information regarding the largest sources of uncertainty: (a) the amount of P that enters the system as part of the imports of coal, due to the large variability in the phosphorus content in the coal used in the USA (Rao and Walsh 1997), followed by (b) the discharges from WWTPs, which is clearly related to the uncertainty of (c) the composition of WWTP influent (similar to the case for nitrogen). Further comparison with other studies and systems can be carried out by

Table 6 Comparison of intensive system characteristics applied to phosphorus

	UCW ($kg\ P\ y^{-1}\ cap^{-1}$)	Other studies ($kg\ P\ y^{-1}\ cap^{-1}$)
P in household wastewater	0.2–1.2	0.8[a], 0.6[b], 0.9[c]
Municipal organic waste	0.15–0.22	0.20[a]
Food consumption	1.3–1.9	1.1[a]
Refuse food (as a percentage of consumed food)	8–17%	18[a], 11%[b]
Use of fodder	4.0–5.5	3.0[b]
P in WWTP effluent	0.02–0.3	0.7[c]
P fixation and deposition	0.02–0.22	0.03[c]

All values reported on a per capita basis

[a] Source Antikainen (2007), case study developed for Finland in the 1990s

[b] Source Neset et al. (2008), scenario for Sweden in year 2000

[c] Source Tangsubkul et al. (2005), illustrating the city of Sydney in year 2000 under the assumption that WWTPs had no P removal

analyzing the intensive characteristics in P terms as shown in Table 6. For instance, it seems that intensive livestock production is more prevalent in the case of the UCW compared to Sweden, on a per capita basis.

Carbon

The energy sector becomes the main actor in the carbon flows estimated by the model, as illustrated in Table 7. All fossil fuels utilized within the system are imported. The largest import of C is associated with gasoline, 1.62×10^6 t C y^{-1}; therefore, it is no surprise that the largest C flux by far is that of emissions from transportation, which accounts for 57% of all emissions originating in local fuel consumption, for residential, commercial, industrial, and transportation purposes, for a total of nearly 3.50×10^6 t C y^{-1}. Of the emissions from transportation, 92% comes

Table 7 List of the most relevant carbon flows in the Upper Chattahoochee Watershed in the year 2000 and estimated standard deviation (s.d.)

Flow number[a]	Flow description	Mean value[b] 10^6 (t C y^{-1})	s.d. (% of the mean)
F_4^{232}	Emissions from local fuel consumption	(3.45)	7.4
F_4^{218}	Emissions from power generation	(1.23)	9.6
F_4^{106}	Imports of wood products	+0.92	6.8
F_4^{148}	Carbon absorption through photosynthesis	+0.63	16.2
F_4^{176}	Feed consumption by livestock	0.36	7.7
F_4^{147}	Carbon losses through metabolic respiration	(0.28)	3.8
F_4^{122}	Local consumption of paper products	0.24	8.0
F_4^{97}	Live trees removal	0.24	6.5
F_4^{271}	Material landfilled[c]	0.21	7.6
F_4^{156}	Total food consumed	0.18	3.9

[a] Refer to Eq. 1 for explanation of the designation of flow numbers and indexes

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

[c] Includes municipal sludge, refuse food, wood products, yard waste, municipal solid waste combustion residual, and CCP

from gasoline combustion, and the remaining 8% from diesel and natural gas. The second flow responsible for the local fuel emissions (after transportation) is related to industrial operations amounting to about 1.17×10^6 t C y^{-1}, or 32%. This leaves 8% due to domestic and 3% from commercial fuel use.

Power generation is responsible for the release of 1.23×10^6 t C y^{-1}; 95% of that comes from coal combustion, while the rest is related to natural gas combustion. Almost 90% of the coal imported, 1.33×10^6 t C y^{-1}, is for power generation and the rest is used for industrial purposes. Carbon in natural gas is imported at a rate of 7.13×10^6 t C y^{-1}, mostly for non-power purposes (92%), including residential and commercial heating, industrial use, and transportation. The second most important sector with regard to carbon flows is the forestry sector, due to the large amount of carbon that is handled in wood material and the upper soil layers. About 50% of the mass of wood products is carbon. The total imports of wood products represents about 0.92×10^6 t C y^{-1}, and some 83% is supplied to the local market, while the rest is used for further processing by sawmills.

In the watershed context, hydrological processes have a limited participation in C mobility, with riverine export being 65×10^3 t C y^{-1} and atmospheric deposition 51×10^3 t C y^{-1} (94% as wet deposition). The variability associated with deposition is quite large, with a standard deviation of about 50% of the mean value, mainly because of the use of a lumped deposition rate for a region that has both rural and urban areas. Deposition decreases significantly as measurements are taken further away from cities, for instance, Lohse et al. (2008) and Kawamura et al. (2001).

Metabolic respiration, included in the study for completeness of the mass balance, is probably an unexpected item in Table 7. However, at 0.28×10^6 t C y^{-1}, it has some significance in respect of the C fluxes in the overall system. Using the allometric approach described by Prairie and Duarte (2007), C release, as carbon dioxide, is estimated to be 95 kg C y^{-1} per person, and for livestock is 456, 5.3, and 124 kg C y^{-1} for cattle, poultry, and swine respectively. Human population and poultry together account for 89% of the net respiration. Although metabolic respiration is not considered a source of greenhouse gases from the perspective of managing carbon emissions, it describes part of the path of the carbon content in food, together with the flows of municipal solid waste and sewerage.

The relative uncertainty of carbon flows is lower than those of the N and P flows, where the sequestration of C due to photosynthesis has the highest level of uncertainty (16%) in association with forest (tree) growth and carbon accumulation in the forest floor.

Energy

Environmental flows are the largest fluxes of energy in and out of the control volume of the Upper Chattahoochee Watershed. The net all-wave radiation (Q^*) of 3.7×10^6 GWh y^{-1}, called here the effective solar energy input, is the major inflow of energy to the system. To put this in perspective, it represents nearly 200 times the total electricity demand of the system (20×10^3 GWh y^{-1}), and over 100 times the energy content of the fuels consumed for non-power generation uses (35×10^3 GWh y^{-1}). About 55% of the solar input is lost via evaporation of water (Q_E), while the rest is distributed between turbulent sensible heat radiation (Q_H), 27%, and storage heat flux (ΔQ_S), 18%.

Despite solar energy being responsible for the largest flows in the system, the UCW relies to a great extent on fossil fuels. There still are questions and uncertainties with regard to how solar energy can be captured and stored, efficiently and in a cost-effective way (Lewis and Nocera 2006). Excluding flows associated with incoming solar energy and other natural processes, Table 8 shows anthropogenic flows of fuels and materials with an important content of energy. In this table, gasoline is the largest flow, and the principal fuel in transportation, responsible for providing approximately 71% of the total demand of fuels for uses other than power generation, in energy terms. 30% of the total demand of energy in fuels (50×10^3 GWh y^{-1}) is used for power generation purposes.

About 30% of the total demand for electricity is locally generated, mostly by the McDonough Power Plant (82%), while the remaining 18% is generated from the two dams on the Upper Chattahoochee River and, to a lesser extent, other renewable sources such as landfill gas and MSW incineration. 90% of the energy content in imports of coal (F_5^{233}) is used for power generation, while the rest is employed for industrial purposes. Natural gas, on the other hand, is mostly used for residential heating, and slightly less than 10% is being used for power generation.

Although the MSA procedure does not reveal how feasible is the recovery of energy from material flows, it gives a measure of the magnitude of energy contained in them that might not be traditionally considered a source of energy. For instance, flows of returned water (F_k^{93}), mostly from power generation, at a higher temperature relative to the average ambient temperature of 15°C, are regarded as having a thermal energy value that could potentially cover about 5% of the total energy demand of the UCW. In the waste management sector, MSW amounts to nearly 3×10^3 GWh y^{-1}, but only 21% of the wood and food portion is incinerated with the purpose of energy recovery.

Table 8 List of the most relevant energy flows (excluding natural flows) in the Upper Chattahoochee Watershed in the year 2000 and estimated standard deviation (s.d.)

Flow number[a]	Flow description	Mean value[e] 10^3 (GWh y^{-1})	s.d. (% of the mean)
F_5^{200}	Imports of gasoline[b]	25	8.6
F_5^{233}	Imports of coal[c]	15	6.8
F_5^{234}	Imports of natural gas[b,c]	14	7.0
F_5^{106}	Imports of wood products	10	7.1
F_5^{205}	Imported electricity[b]	9	8.1
F_5^{93}	Water returned to surface sources	(5)	7.4
F_5^{176}	Feed consumption by livestock	5	5.2
F_5^{295}	Surface runoff that reaches the river (output)	(4)	10.2
F_5^{271}	Material landfilled[d]	3	6.7
F_5^{156}	Total food consumed	2	4.5

[a] Refer to Eq. 1 for explanation of the designation of flow numbers and indexes

[b] Includes domestic, commercial, industrial, transportation users

[c] Includes power generation and industrial users

[d] Includes municipal sludge, refuse food, wood products, yard waste, municipal solid waste combustion residual, and CCP

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

Table 8 also indicates the level of uncertainty attaching to anthropogenic flows, which in the case of energy flows is relatively low, i.e., less than 10%. Although not shown in the table, the largest degree of uncertainty is in fact associated with 'Storage heat flux', ΔQ_S, reaching 35%, possibly as a result of the amplification of uncertainties in Eq. 4, since the term is estimated by differencing.

System-wide perspective and multi-sectoral implications

System-wide perspective

These results can be presented from an alternative perspective in an aggregated form, by classifying flows into five categories: resources (inputs), products (useful outputs), air emissions, aquatic emissions (to surface and ground sources), and wastes (landfilled material). From this, a system-wide accumulation term can be derived, as shown in Fig. 7. For nutrients there is a positive accumulation, but not for water

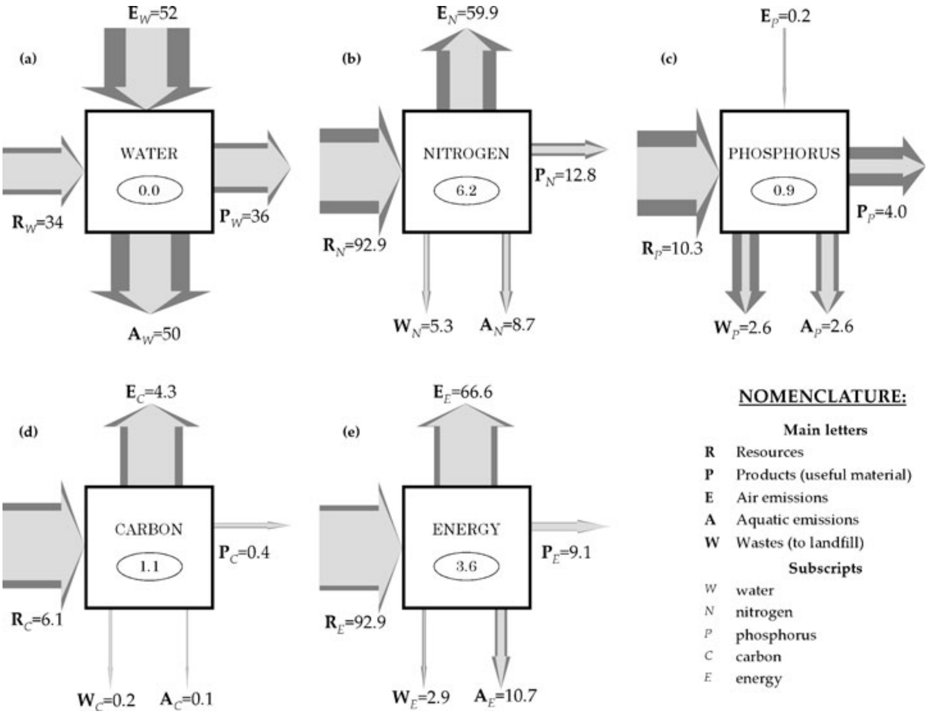

Fig. 7 Mean flows of water, nitrogen, phosphorus, carbon, and energy classified and aggregated as resources (**R**), products (**P**), air emissions (**E**), aquatic emissions (**A**), and wastes (**W**). Accumulation within the UCW-MA system (depicted by ovals) is calculated as the difference between average input and output fluxes. The *grey code of arrows* represents the variability of each aggregated flow, where dark is the upper bound and light is the lower bound (with 90% confidence). Material flows are expressed in terms of mass as 10^3 t y^{-1} for N and P , and 10^6 t y^{-1} for carbon. Water is represented in terms of volumetric flow m^3 s^{-1} and energy in 10^3 GWh y^{-1}

or energy. Consistent with other studies, e.g., Kaye et al. (2006) and Tangsubkul et al. (2005), urban areas and human-managed watersheds behave as sinks of N and P. For instance, the UCW stored N and P at a rate of 19.6 and 3.7 kg ha^{-1} y^{-1} respectively, which represents about 60% of the estimated values for the Potomac River Basin (Jaworski et al. 1992). The Potomac Basin has 40% of its area dedicated to agriculture, compared to 10% for the UCW, suggesting that agriculture might play an important role in the accumulation of nutrients, which in turn could be translated into an increased potential for non-point source pollution in the future. Expressed in terms of the flow of resources entering the system, the accumulation of carbon is the largest, with 18%, compared to N (7%) and P (12%). The two processes contributing to this level of carbon retention are photosynthesis and wood products (including timber, paper, cardboard, and plywood).

Figure 7 reveals that N, C, and energy have a dominant "upward" path, i.e. from resource use to atmospheric emissions, while P tends to be associated with flows of water, waste, and products (downward and horizontal). This could be relevant for resource management and influence the selection of policies or technologies.

In terms of uncertainty, Fig. 7 is consistent with the finding that natural flows—to and from the environment—exhibit significant uncertainty. In the case of water it is clear that environmental fluxes bear the largest uncertainty, i.e., those associated with runoff, precipitation, and evapotranspiration, while in the case of P most of the uncertainty is associated with the resources entering the system (coal-bound) and its distribution after use into products and wastes (landfill material).

Ninety-five percent of the N resource inputs ($\mathbf{R}_N$; in Fig. 7) to the system are accounted for in fodder, fuels (coal and natural gas), and inorganic fertilizer. 90% of the total N flux released to the atmosphere is from fuel-bound N and emissions from WWTPs. A large proportion of the output N products ($\mathbf{P}_N$) from the UCW is represented by meat (mainly poultry) and poultry litter exported as a nutrient source. Emissions to aquatic systems are the sum of the various sources of leachate and surface runoff totaling more than 8,000 t N y^{-1}. The data suggest that accumulation is mostly related with the food sector, more specifically, fertilizers and animal feed. As for N, the food and energy sectors are the most significant for phosphorus flows. The largest P inputs can be identified as fodder import (6,200 t P y^{-1}), P in coal (2,000 t P y^{-1}), and inorganic fertilizers (1,300 t P y^{-1}). The atmospheric component of P is associated with deposition and, to a lesser extent, particulate emissions from coal combustion. Aquatic emissions are for the most part contributions from surface runoff and soil infiltration, for a total of 2,200 t P y^{-1}. Discharges from WWTPs and other industrial operations are less significant, being slightly over 200 t P y^{-1}. The main UCW output products containing P are manure and meat, at 2,500 t P y^{-1} and 900 t P y^{-1} respectively, making up 85% of all P in the system's products. Similar to N, it would be appropriate to say that the food sector is responsible for the accumulation of P.

Carbon, on the other hand, is predominantly influenced by the energy sector. About 70% of the C that enters the system is lost as air emissions—unquestionably from fuel combustion. Roughly 92% of all the materials exported as (beneficial) *products* comprise recycled paper (164×10^3 t C y^{-1}), wood products (88×10^3 t C y^{-1}), and manure (73×10^3 t C y^{-1}). Hence, in the case of C, there is a shift from only food and energy—as observed for N and P—to energy and forestry. After losses to the atmosphere, hydrosphere, and lithosphere, 20% of the input C remains in the UCW system. Because of the characteristics of the carbon cycle, the analysis for identifying the relevant causes of accumulation requires examination in detail of the nature of the C inputs to the system. A large portion thereof is comprised of fossil fuels and biofuels (4×10^6 t C y^{-1}), biomass ($1{,}600 \times 10^3$ t C y^{-1}), including 42% for fuel purposes, animal feed (350×10^3 t C y^{-1}), and food (140×10^3 t C y^{-1}). Carbon emissions from biomass used as fuel (630×10^3 t C y^{-1}) are almost compensated for by the carbon sequestered by photosynthesis: thus, the materials responsible for accumulation are mostly wood products, possibly associated with construction materials (Kennedy et al. 2007) and to a lesser extent, the manure generated from livestock operations. The total emission of carbon to the atmosphere can be expressed in terms of CO_2 as 12 t CO_2 cap^{-1} y^{-1}, which is comparable to the emissions estimated for the Greater Toronto Area (GTA) in 1999, of 14 t CO_2 cap^{-1} y^{-1} (Sahely et al. 2003). In terms of surface area, GTA has larger carbon emissions (10,000 t CO_2 km^{-2} y^{-1}) compared with the UCW (4,000 t CO_2 km^{-2} y^{-1}), which is consistent with the difference in population density of these two regions: 700 cap km^{-2} for the GTA and 320 cap km^{-2} for the UCW.

The solar energy entering the system (Q^*) heats urban and land surfaces during daytime, but is mostly lost due to turbulent sensible heat flux (Q_H) and stored heat flux (ΔQ_S). Therefore, the net energy flux emitted is the result of anthropogenic heat releases ($Q_F - Q_W$). The term ΔQ_S can be interpreted as a measure of the available heat that contributes to the urban heat island (UHI) effect, which has potential impacts on energy demand and air quality. Thus a system with a larger ΔQ_S per unit area has a larger potential for experiencing the UHI effect and exhibiting higher temperatures compared to neighboring areas. Metro Atlanta, for instance, can have temperatures 5°C higher than its surrounding areas (Dixon and Mote 2003). This energy can be harvested by emerging technologies, such as heat mining from pavements using fluids flowing in pipes within the pavement (Mallick et al. 2009). Similar to the energy balance, water does not experience accumulation within the system, since the net inflow of water (precipitation minus evapotranspiration) exits the system in the form of runoff and infiltration. On the other hand, almost all water withdrawals are returned as products, i.e., treated water discharges and inter-basin exports. The lack of water accumulation is typical of urban areas (Sahely et al. 2003), particularly when reservoirs or groundwater storage are not considered part of the system.

Multi-sectoral implications

The results indicate that natural flows are predominant in terms of energy and water, but anthropogenic flows are more relevant for the movement of nitrogen, phosphorus, and carbon. From a different perspective, the multi-sectoral approach allows the identification of which sectors are the key participants in the metabolism of a certain material or substance. This is critical for revealing the sector in which a policy action, a corporate move, or an entrepreneurial initiative can have the largest impact on the management of flows in the form of resources, products, emissions or discharges. Following the same logic, the MSA framework offers the opportunity for assessing the implications of change in one sector—represented possibly by shifts in management practices, new regulations, or the implementation of new technologies—for changes in another sector. Although the demonstration of this application of MSA is shown elsewhere (Villarroel Walker et al. 2012), it is possible to imagine the ripple effect of, for instance, the implementation of the urine separation technology (in the water sector) on the food industry and the energy sector. The former arises through the local production of about 4,000 t N y^{-1} of inorganic fertilizer, namely struvite $MgNH_4PO_4 \cdot 6(H_2O)$, and the latter by reducing the energy demand of activated sludge plants (Wilsenach and Van Loosdrecht 2003; Maurer et al. 2003; Larsen and Lienert 2007). Other actions might affect a single sector but have great impact on the overall metabolism nonetheless. For example, Georgia Power has ongoing projects that will allow the McDonough power plant to phase out their coal-fueled process, with a nominal capacity of 540 MW, in favor of a 2520 MW natural gas combined-cycle process (GAPOWER 2011b). Given that the latter process has a much better efficiency, it is expected that air emissions and water usage will be reduced on a per unit energy basis. Carbon emissions would be reduced from 2300 to 830 t C y^{-1} per MW of installed capacity and the UCW would be independent of external sources of electricity. However, generation capacity is being expanded almost five times, which will result in an overall increase of carbon emissions by more than 60% and of water use by a factor of nearly 4. The new process also translates into a reduction of water withdrals by two thirds per unit of energy generated compared to the coal process (Feeley et al. 2008). However, as for atmospheric emissions, because the plant capacity is being increased, the overall water use will increase.

The extent to which a sector is responsible for the movement of a resource, within the internal *metabolism* of the system, can be expressed by the magnitude, i.e., mass and energy, of the flows that enter the sector. For the UCW case, this is reflected in Fig. 8 where the amounts of nutrients, water, and energy handled by each sector are aggregated and compared relative to other sectors. The energy sector is responsible for nearly 60% of water withdrawals, followed by the water sector that supplies residential, commercial, and industrial users. The food sector, which includes irrigation and water content in food, is slightly more than 1%. In terms of nitrogen, the energy sector is also predominant, with 45%, mainly because of the

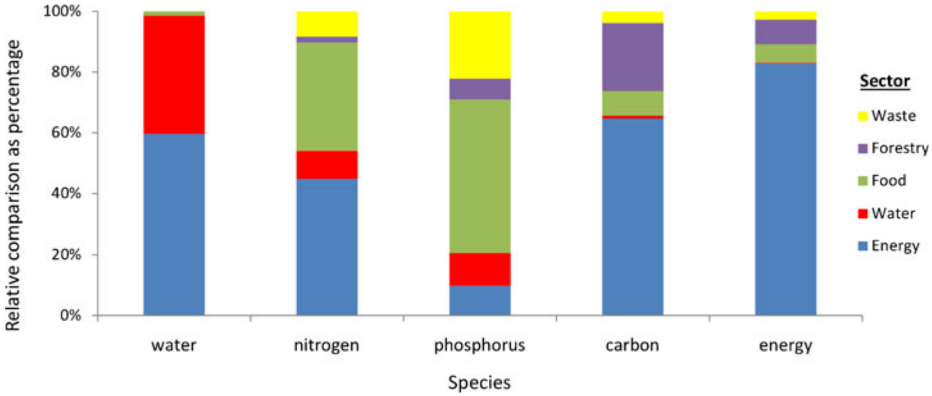

Fig. 8 Relative comparison of inputs of materials and energy among sectors where 100% is the aggregation of the inputs to all sectors

nitrogen content in coal and natural gas. The food sector follows with 36%, largely by the poultry industry present in the region. Nitrogen is a nutrient that is often released in a gaseous form, hence the reason why the water sector has a relative magnitude of 9% only, handled by sewers and septic tanks. Most of the phosphorus in the UCW moves within the food sector, with 50%, followed by the waste management sector (22%) which handles refuse flows from the food sector, water sector (sludge), forestry (disposed paper, wood, and yard waste), and the energy sector (CCP). Unsurprisingly, the energy sector is where most of the carbon and energy flows are managed, with 65 and 78% respectively. From the resource management point of view, Fig. 8 gives a glimpse of the specific sectors that have to be investigated for the recovery of a given material. For instance, the food sector seems to be a good candidate for improving phosphorus management in the UCW. Similarly, the energy sector could be a prominent start for addressing issues of the circularity of nitrogen and carbon, as well as consumption of water and energy flows. This kind of analysis can suggest positive policy/technology interventions that modify the way sectors manage resources and have a direct effect on the internal metabolism of the system. Beyond the boundaries of the system, these seemingly adequate interventions could be assessed for their positive or negative impact on relevant footprints, e.g., carbon, greenhouse gas emissions, or ecological.

Conclusions and future work

Cities—and human-managed areas in general—have the great opportunity, and some will say the responsibility, of overturning the current perception of them: from that of environmentally insulting structures to that of an accumulating set of processes and activities that result in beneficial flows to the surrounding environment, i.e., flows that will nourish other systems instead of degrading them. A key step towards this vision is understanding and identifying important economic and industrial players in the metabolism of the system.

Integrated multi-sectoral approach: Systems analysis framework

In the present work, human-managed systems are divided into five sectors: water, energy, food, forestry, and waste management, as a means of structuring their complex web of processes and flows. The multi-sectoral approach also allows the practitioner to identify what sectors, flows, and processes are more critical with respect to a certain substance, which should translate into a better understanding of the system itself, and possibly better ways of addressing resource and environmental issues from the management and policy perspectives as well. At this point, the purpose of the framework described herein is mostly that of accountancy, that is, to estimate the magnitudes of flows of resources, products, emissions, and wastes, as well as within-system accumulation, for a total of five *species*: water, nitrogen (N), phosphorus (P), carbon (C), and energy. The multi-sectoral structure of the MSA allows identification of the processes, and sectors, responsible for demand or generation of flows and stores. Through the Regionalized Sensitivity Analysis (RSA) procedure, the MSA offers additional information with regard to the variability and uncertainty of the results, which is critical for developing robust policies and sound decisions. Furthermore, the uncertainty analysis will also reveal those areas where more research is needed in order to reduce levels of uncertainty.

Insights from the case study: The Upper Chattahoochee Watershed

The purpose of the case study has been to provide a rather comprehensive view of the flows of water, nutrients (N, P, and C), and energy associated with the Upper Chattahoochee Watershed (UCW) and to demonstrate that the proposed methodological framework can provide useful information for better understanding of the internal metabolism of a system.

The largest water withdrawal is for power generation processes (energy sector), followed public supply withdrawals which provide water for domestic (53%), commercial (23%), industrial (15%), and public uses (9%). The demand for energy in fuels is mostly for uses other than power generation (70% of the total), i.e., transportation (55%), industrial (31%), residential (10%), and commercial users (4%). The foregoing agrees with the fact that gasoline constitutes the largest demand for fuel in the region. The major flow for nitrogen, on the other hand, is associated with imported fodder for livestock (food sector), as a consequence of the prominence of the poultry industry in the region. The emissions from power and non-power users are quite relevant, making the energy sector responsible for most of the movement of nitrogen. Phosphorus is clearly controlled by flows associated with the food industry—represented by poultry production and land fertilization—and the consequences of people (consuming food) using the water sector as their waste carrier (municipal sludge). Urine contributes a fourth of all the P recovered by WWTPs. In the form of CCP, the energy sector handles an amount of phosphorus comparable to the water sector.

For the year 2000, the UCW exhibited no accumulation of water, but on the other hand, it shows a positive accumulation of N, P, C, and energy. The analysis suggests that the accumulations of N and P are related to the food sector, namely the use of fertilizers, while in the case of C and energy, it seems to be associated with the sequestration process in forests and the accumulation of wood products—possibly in the construction and forestry industry.

Further work and applications

The results of the MSA, used simply to gauge the *status quo*, have made clear the interconnections among the five sectors, and the relevance of each *species* of interest (H_2O, N, P, C, and energy) within each sector. The information generated by the MSA framework can be used also as a prospective (futures-oriented) tool at different levels: (a) personal (human behavior and decisions), (b) government (formulation of policy and regulations), and (c) corporate (technology assessment). Because the methodology involves the interaction between the system and the environment, it is also possible to introduce into it the influence of external features, e.g, climate change. In addition to the above, the present analysis can be extended to include not only direct flows but also indirect flows, making MSA a tool for investigating transboundary flows of materials associated with the internal *metabolism* of a region.

The flexible computational platform used to develop the MSA, i.e., MATLAB®, facilitates its application as a prospective or change-oriented tool. This approach, which goes beyond the stationary (snap-shot) mode, could be used for the analysis and comparison of transition paths (scenarios) towards sustainability objectives. Additionally, experimenting with transition paths will allow one to better illustrate and investigate the synergies and antagonism among sectors. The MSA embodies a comprehensive understanding of the complexity of the system's structure and the synergy among its parts, as required for the evaluation of structural and/or management transitions (Lang et al. 2006). Material and energy flows can be used to elaborate socio-economic indicators (Azar et al. 1996), which are particularly useful for scenario comparison. Furthermore, indicators can be formulated based on efficiency and effectiveness principles, reflecting our broader vision of the *Cities as Forces for Good* (CFG) project.

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